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for the

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FACTORS AFFECTING THE STARTING CHARACTERISTICS OF GAS-TURBINE ENGINES

By Lewis Laboratory Fuels Panel

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

This report summarizes the effects of fuel volatility and engine design variables on the problem of starting gas-turbine engines at sea-level and altitude conditions. The starting operation for engines with tubular combustors is considered as three steps; namely, (1) ignition of a fuel-air mixture in the combustor, (2) propagation of flame through cross-fire tubes to all combustors, and (3) acceleration of the engine from windmilling or starting speed to the operating speed range.

Pertinent data from laboratory researches, single-combustor studies, and full-scale engine investigations are presented on each phase of the starting problem.

INTRODUCTION

As part of a general program on combustion research, the NACA Lewis laboratory is conducting numerous research investigations pertinent to the problem of starting gas-turbine engines at sea level and altitude. The ultimate objective of these researches is to contribute, through better understanding of the basic factors in engine starting, to the broad objective of achieving greater reliability and excellence of performance in gas-turbine engines.

The starting investigations being conducted by the NACA are concerned with the basic combustion processes involved in starting and the proper application of these processes to the actual engine. Preliminary phases of these investigations dealing with processes such as flame propagation, inflammability limits, and minimum ignition energies have been reported in references 1 to 6. Additional studies reported

in references 7 to 14 indicate the function of these basic processes in the environment of full-scale gas-turbine engines and single-combustor experimental apparatuses.

Although these reported investigations do not present a complete answer to the starting problem, certain design characteristics and fuel characteristics are reasonably well-defined. For this reason and because of the importance of gas-turbine engine starting in the current military picture, a summarization of the existing research data on the starting problem is considered timely. Accordingly, it is the purpose of the present report to review the results of NACA gas-turbine engine starting investigations and other available information.

The discussion of starting is presented in three parts paralleling the engine starting process: (1) ignition of the fuel-air mixture in the combustor, (2) propagation of flame to all combustors, and (3) acceleration of the engine from the windmilling or starting speed to the operating speed range. Each of these phases of the starting process is discussed with consideration for the influence of engine design variables and fuel variables.

THE IGNITION PROCESS

Ignition in gas-turbine engines must occur properly and reliably at altitude conditions as well as at sea-level conditions. Ignition at altitude would be required if the blow-out limit of the engine were exceeded and for the starting of engines that were intended for use only during a selected portion of a military flight.

The fact that the ignition process must function at sea-level and altitude conditions necessitates a thorough study of the influence of many factors on the starting characteristics of the gas-turbine engine. In order to better understand the role of these factors in the ignition process, investigations have been conducted in laboratory apparatuses, single combustors from gas-turbine engines, and full-scale engines under conditions comparable to those encountered in service. The variables receiving primary attention in these investigations were fuel-air ratio, pressure, and velocity in the vicinity of the spark discharge. Considerations of fuel-air-ratio effects also involved an evaluation of fuel volatility and the nature of the fuel spray.

Factors Affecting Minimum Ignition Energy

The effects of fuel-air ratio, pressure, and velocity on spark energy required for ignition were investigated in laboratory apparatuses

(references 6 and 15) using propane as a fuel. Gaseous propane was used in order to eliminate the effects of variables involved in fuel vaporization. The ignition systems used in these investigations were arranged so that spark energy could be measured and varied over wide limits.

Fuel-air ratio. - The effect of fuel-air ratio on energy required for ignition of a quiescent mixture of propane and air is shown in figure 1, taken from reference 15. The data were obtained with the spark electrodes set at the optimum spacing to allow the minimum energy for ignition. It is apparent from this figure that the minimum energy required for ignition occurs at a fuel-air ratio richer than stoichiometric and that, for fuel-air ratios richer or leaner than the point of minimum energy, the energy required for ignition is considerably higher.

In interpreting these data in terms of the condition that exists in a gas-turbine combustor, it is obvious that ignition of the fuel-air mixture will occur only if the energy available at the ignition source is sufficiently high to cause ignition at any fuel-air ratio that may be present in the vicinity of the ignition source. Moreover, ignition will occur only if the fuel-air ratios that may be present in the vicinity of the ignition source are within the limits of inflammability indicated by relations such as that of figure 1.

Velocity. - The minimum energy required for ignition is also influenced by the velocity of the fuel-air mixture that passes the ignition source. Figure 1 was determined from tests with quiescent fuel-air mixtures; figure 2 taken from reference 6 illustrates the variation of the required energy with velocity. In this figure, it is seen that as the velocity increases at constant fuel-air ratio the energy required for ignition becomes greater. An increase in velocity from 10 to 55 feet per second requires a two-fold increase in energy for ignition. These data were obtained at reduced pressure; however, the trend remains the same at other pressures. The spark gap width shown in figure 2 is not the optimum gap spacing that was used in figure 1.

It is of interest to note that at 0.1-atmosphere pressure (fig. 2), even with a homogeneous gaseous mixture of fuel and air, the energies required for ignition are above those provided on some turbojet engines. For example, at a gas velocity of 20 feet per second, an energy of about 0.04 joule is required for ignition. An average spark energy provided on some turbojet engines is 0.025 joule.

It seems unlikely that turbojet engines could be started at very high altitudes with such low spark energies. The influence of spark rate, however, must also be considered, as will be shown in a subsequent section.

Pressure. - The effect of pressure on the minimum energy required for ignition is shown in figure 3 where energy is plotted against pressure. As pressure is reduced from 1 atmosphere to approximately 0.1 atmosphere, the energy required to ignite a quiescent mixture of propane and air increased more than 100 times. These results were obtained under conditions where the fuel was completely vaporized, the fuel-air mixture was correct, and the mixture was static. In an engine under conditions where vaporization is far from ideal and where the fuel-air mixture has a velocity dependent on the flight speed of the airplane, higher energies would be required for ignition. The spark energy of 0.025 joule provided in some current turbojet engines is marginal or too low as indicated by the horizontal broken line in figure 3.

The vertical dotted line in figure 3 shows the pressure in the combustor of a J33-A-23 turbojet engine at 60,000 feet at 0.6 Mach number at an engine windmilling speed of 1000 rpm. For this condition, it is indicated that the ignition energy required should be about 100 times the energy required at sea level.

Single-Combustor Investigations of Ignition

The foregoing discussion illustrates the effect of several factors on ignition energy in simplified laboratory apparatuses. The next step is to determine whether the general trends still apply in the more complex gas-turbine combustor. In addition to the parameters already considered, the effects of temperature, fuel volatility, and location of ignition source were investigated in the actual combustors or engines. The results of these investigations are discussed in this section and in the succeeding section on full-scale engine studies.

Fuel volatility and spark energy. - An investigation has been conducted on a J33 single combustor (reference 14) to determine the relation between fuel volatility and the required spark ignition energy. The fuels investigated were a JP-3 type fuel (NACA fuel 50-174), a fuel having a 1 pound per square inch Reid vapor pressure (NACA fuel 49-246) obtained by removing volatile components from a JP-3 stock, and a JP-1 fuel (NACA fuel 48-306). The physical properties of these fuels are given in table I and the distillation curves are shown in figure 4.

The combustor was equipped with a variable-area fuel nozzle of the type described in reference 16 for the purpose of providing a good spray at low fuel flows. The fuel and air systems were provided with means for reducing the temperature to low values.

The type of spark plug used in this investigation was a unit specified for the J33-A-23 engine. The electrodes eroded very rapidly during tests in which high spark energies were investigated.

The procedure used in attempting ignition consisted in setting the air flow at the desired value, energizing the spark, and gradually opening the fuel throttle from closed to full-open. This technique was used in an effort to provide a fuel-air mixture satisfactory for ignition.

The ignition circuit was arranged so that the energy per spark could be continuously varied from 0.0001 to about 16 joules. The voltage, capacitance, and sparking rate could be independently varied. The energy was varied by varying both voltage and capacitance.

The effect of sparking rate on ignition in the single combustor was briefly investigated with the 1-pound Reid vapor pressure fuel by maintaining the air flow constant and varying the sparking rate. Some of the results are shown in figure 5, where spark energy is plotted against combustor-inlet pressure. Ignition could be obtained above and to the right of the lines. At a spark energy of 0.025 joule with 3 sparks per second, ignition could not be obtained below a pressure of 26 inches of mercury absolute; whereas at a spark rate of 200 sparks per second, ignition could be obtained down to a pressure of 15.7 inches of mercury. At energies above 0.5 joule, the differences in ignition limits were small between sparking rates of 8 to 200 sparks per second.

As previously mentioned, the spark electrodes of the plugs used in this investigation deteriorated very rapidly at high spark energies; and inasmuch as 8 sparks per second seemed to be a sufficient rate at the higher energies, the spark rate throughout the investigation was maintained constant at 8 sparks per second.

The conditions required to provide ignition in a gas-turbine engine at low temperatures are of considerable importance; therefore, an attempt was made to simulate the environment to be encountered at ground-level cold-weather conditions and to determine the minimum spark energies required to ignite the three fuels.

The inlet pressure, air flow, and temperature to the combustor, at a given sea-level ambient temperature, are shown in figure 6. The fuel temperature in this investigation was maintained at ambient temperature.

The results obtained under these conditions are shown in figure 7 where the minimum energy in joules per spark is plotted on a logarithmic scale against the sea-level ambient temperature. It is seen in figure 7 that as the ambient temperature is decreased, the energy required for ignition increases. At -50° F, the most easily ignited fuel, JP-3, required about 0.17 joule for ignition. At temperatures above 0° F, the energies required to ignite the JP-3 fuel and the 1-pound Reid vapor pressure fuel were about the same; however, at temperatures below 0° F the 1-pound fuel required considerably more energy for ignition than did the JP-3 fuel. Thus, low temperatures seem to have a more adverse effect on the ignition qualities of a 1-pound fuel than on the ignition qualities of a JP-3 fuel. The JP-1 fuel required more energy for ignition than the other fuels throughout the temperature range investigated.

Care should be exercised in the interpretation of figure 7 in terms of actual service operation of a gas-turbine engine because of the influence of spark rate on ignition. As previously mentioned, the spark rate used in these tests was 8 sparks per second, whereas in actual engines the spark rate may be as high as 400 to 800 sparks per second, and the rate has an important effect when low energies are used. For this reason, JP-1 might be ignited in an engine at approximately 80° F even though the energy available at the spark plug is somewhat less than the required energy indicated by the curve for JP-1 fuel.

The results shown in figure 7 do not indicate whether fuels of different volatility will require different energies to ignite at higher spark rates. However, the results of other investigations to be discussed later in this report indicate that the trends shown in figure 7 are correct for higher sparking rates.

An additional investigation of the effects of fuel and air temperature on ignition has been reported in reference 13. In this investigation, the minimum fuel flow required for ignition was determined for three fuels at controlled fuel and air temperatures. The fuel and air temperatures were equal for all of the starts attempted in the investigation. A swirl-type fuel nozzle of 40-gallon-per-hour capacity was used. The spark energy was 0.015 joule at a spark rate of 60 per second.

The effect of fuel and air temperature on the minimum fuel flow required for ignition is shown in figure 8 for a fuel having a Reid vapor pressure of 7 pounds per square inch, another of 4.5 pounds per

square inch, and JP-1 fuel. The inlet-air conditions were set to simulate sea-level conditions at an engine starting speed of 1600 rpm. Ignition could be obtained at fuel flows to the right of the lines. In considering the curves (fig. 8) for each fuel, it is seen that as the temperature of fuel and air is reduced from 110° to -16° F the fuel flow required for ignition is increased by a factor of 2.4 times for the 7-pound fuel (NACA fuel 49-245) and by a factor of 3.5 times for the JP-1 fuel (NACA fuel 48-306). This result tends to confirm the observation previously made that low temperatures seem to affect the ignition qualities of a low-volatility fuel more adversely than the ignition quality of a volatile fuel.

The results in figure 8 indicate that, as the temperature is lowered, the increased fuel flow is necessary to provide an inflammable mixture in the vicinity of the ignition source. The exact magnitude of this fuel-air mixture ratio cannot be ascertained; however, preliminary equilibrium calculations suggest that a constant fuel-air ratio of vaporized fuel to air is provided throughout the temperature range investigated. There is a slight tendency for these calculated fuel-air ratios to decrease as the temperature is decreased even though the required fuel flow in figure 8 increases.

The data in figure 8 have been replotted in figure 9 as critical fuel flow required for ignition as a function of the 10-percent evaporated temperature of the fuel with lines of constant fuel and air temperature. Because of the apparent relation between the fuel volatility and the fuel flow required for ignition, figure 9 provides a convenient plot for estimation of starting characteristics of various fuels at sea level in a J33 combustor.

In addition to the sea-level starting tests discussed in the preceding paragraphs, the investigation (reference 13) also included an evaluation of the starting characteristics of the three fuels at altitude conditions. These results shown in figure 10 indicate that the fuel flow required for ignition increases as the altitude increases particularly in the case of the fuel having a Reid vapor pressure of 4.5 pounds per square inch (NACA fuel 49-162) and in the case of the JP-1 fuel. The highest altitude at which ignition was obtained for each fuel is not an ignition limit but is the terminal point of investigation for the particular fuel.

Extremely high over-all fuel-air ratios are required for ignition of JP-1 fuel at an altitude of 20,000 feet. The 7-pound fuel was ignited at a fuel-air ratio of about 0.02 at 20,000 feet and the 4.5-pound fuel, at a fuel-air ratio of 0.045; whereas JP-1 fuel required

a fuel-air ratio of 0.08 for ignition at the same altitude. Although these data are not directly applicable to full-scale engine ignition, they do indicate that marked differences may be anticipated with fuels of different volatility.

Effect of pressure on ignition. - In order to demonstrate the effect of pressure independent of temperature, the inlet-air temperature was held at -10° F and the fuel temperature was held at -40° F while the pressure was varied (reference 14). The minimum energy required for ignition was determined at a series of air flows for the three fuels. A typical plot is shown in figure 11 for the JP-3 fuel. Spark energy is plotted against combustor inlet pressure for various air flows. Ignition could be obtained above and to the right of the curves. Similar data were obtained for the 1-pound Reid vapor pressure fuel and for JP-1. The data for all three fuels are replotted in figure 12 as inlet pressure against air flow for several values of ignition energy. Ignition could be obtained above and to the left of the constant-energy lines. It is apparent in this figure that at low pressures ignition can be obtained over a wider range of air flow as the spark energy is increased. This result is consistent with the results of figure 2, in which it was found that high spark energies were required for ignition at high velocities. The figure shows results obtained with 0.025 joule at a sparking rate of 8 per second with a solid line, and results obtained with 0.025 joule at a spark rate of 200 per second are shown by the broken line. The higher spark rate gave ignition at lower pressures than could be obtained with a rate of 8 sparks per second, but higher spark energies allowed ignition at lower pressures and higher air flows.

The burning limits of the J33 combustor with each fuel are shown in each part of figure 12. At low air flows, ignition with a 10-joule source can be obtained almost to the blow-out limit for all three fuels. At higher air flows, ignition could be obtained to within about 4 inches of mercury of the burning limit.

The ignition limits of the three fuels are compared in a series of plots in figure 13. Combustor inlet pressure is plotted against air flow for energies of 0.025, 1, 2, 4, and 10 joules. The ignition limits of JP-1 fuel show a minimum pressure limit at an intermediate air flow but the JP-3 fuel and the 1-pound fuel show a consistent trend in that as air flow is increased the limiting pressure for ignition is raised.

At low spark energies the JP-3 fuel can be ignited at lower pressures than the 1-pound fuel, but as spark energy is increased, the ignition limits tend to become independent of fuel volatility. At spark

energies of 1 and 2 joules, the JP-3 fuel ignited at about 3 inches of mercury lower pressure than the 1-pound fuel. At 4 joules the ignition limits for the two fuels are very close together and at 10 joules the limits of the two fuels are the same.

The ignition limits just discussed were obtained in a single tubular combustor that was equipped with a variable-area fuel nozzle, and the results are not necessarily indicative of results to be obtained in full-scale engines. The results, however, do indicate the possibility of eliminating differences in ignition limits due to fuel volatility by use of spark energies above 2 to 4 joules. In order to obtain ignition at high air flows at pressures near the burning limits of the combustor, spark energies of 10 joules or higher are indicated.

Full-Scale Engine Investigation of Ignition

The effect of various factors on the ignition process in starting of full-scale engines has been investigated by the NACA during a number of programs conducted in an altitude wind tunnel, altitude tanks, and in flight. Among the factors investigated were spark energy, spark location, fuel volatility, and fuel and air temperatures. Pertinent details of the apparatuses and operating conditions are given in table II.

The altitude ignition limits of turbojet engines vary widely; consequently, a comparison of these limits for several engines provides a reasonable basis for the subsequent discussion of effects of various factors on starting limits. In figure 14 the altitude ignition limits for five engines are compared. The engines with centrifugal compressor show quite different ignition characteristics. The J33 engine with JP-1 fuel shows no sensitivity to flight Mach number; whereas the Nene engine altitude ignition limit decreases rapidly with increasing flight Mach number. The drop in altitude limit at low Mach numbers for the J33 engine results from too low a fuel pressure for the pump at the windmilling speed to produce a good fuel-spray pattern.

The engines with axial-flow compressors are compared using more volatile fuels: about 6-pound Reid vapor pressure fuels (NACA fuel 50-246 and 50-237). Again, there is considerable difference in the magnitude of the effect of flight Mach numbers. The J35 engine showed the greatest sensitivity to flight Mach number. In comparison with the J47 engine, the J35 engine has a lower spark energy and less favorable spark-electrode location. The effect of these variables will be discussed in the following paragraphs.

Effect of spark energy. - To determine the effect of spark energy, spark voltage, and spark repetition rate on ignition limits of a complete engine installation, a variable-energy capacitance-discharge ignition system was used on the J35-A-17 turbojet engine in an altitude chamber (unpublished NACA data). The system was designed so that the spark-input variables could be independently adjusted. With this system the spark energy could be varied from 0.15 to 10 joules per spark, the voltage from 5000 to 15,000 volts, and the repetition rate from 2 to slightly over 100 sparks per second. With this system installed, altitude ignition limits were obtained with the engine windmilling at a simulated flight Mach number of 0.6 with a fuel having a Reid vapor pressure of 1.1 pounds per square inch (NACA fuel 49-246). This Mach number was considered to be approximately the highest and, consequently, the most difficult at which starts would be made in flight. Fuel and air temperatures were maintained at approximately standard ambient values down to temperatures of about -50° F.

The effect of spark energy and repetition rate on altitude ignition limits is shown in figure 15 for a spark potential of 5000 volts. The ignition limit of the standard J35-A-17 ignition system is included for comparison. At a repetition rate of 2 sparks per second, an increase in spark energy from 0.15 to 3.2 joules per spark raised the ignition limits from 20,000 to 50,000 feet. A further increase in energy to 4.7 joules per spark afforded ignition to the altitude exhaust limits of the chamber, approximately 60,000 feet. In most cases, there was an increase in the altitude ignition limit of 10,000 to 20,000 feet as the spark repetition rate was raised from 2 to about 40 sparks per second. Only in one case did an increase in repetition rate above 50 sparks per second further extend the ignition limits. In comparison with the limits obtained with high energy and relatively low repetition rates, an altitude ignition limit of 25,000 feet was encountered with the standard ignition system having a spark energy of 0.019 joule per second at 800 sparks per second and 15,000 volts.

The effect of spark voltage on the altitude ignition limits is shown in figure 16 for several repetition rates. At repetition rates up to 50 sparks per second, an increase in voltage from 5000 to 14,000 volts raised the altitude limit by as much as 20,000 feet in some cases. With a repetition rate of 100 sparks per second, the effect of spark voltage was not so apparent.

The effect of ignition energy on starting was investigated to a limited extent in a J34-WE-32 engine installed in an altitude wind tunnel (unpublished NACA data). The starting limits were obtained with the standard ignition system and with a low-voltage high-energy system using a surface-gap type spark plug.

The combustor on this engine is provided with 60 fuel-spray nozzles that deliver a hollow-cone spray at an angle of 80°. The flow capacity of the nozzles is rated at 7 gallons per hour at a pressure of 100 pounds per square inch. The fuel nozzles had been operated in the engine about 153 hours preceding the starting investigation. An inlet-air temperature of about 15° F and a fuel temperature of 80° F existed during the starting tests. These tests were made with 80-octane clear gasoline (NACA fuel 50-237).

The standard ignition system for the J34-WE-32 is composed of two units, one for each of the two spark plugs provided in the combustor. Each unit consists of a coil, condenser, vibrator, and spark plug. The coil supplies the high voltage required for ignition during the 30-second interval provided by a control timer.

The results obtained with the standard ignition system are shown in figure 17(a). With this system the engine could be ignited and accelerated to an altitude of 42,500 feet at a Mach number of 0.4. At higher Mach numbers the engine could not be ignited at 35,000 feet but could be ignited at 25,000 feet up to Mach numbers as high as 1.075.

The results obtained with the high-energy ignition system are presented in figure 17(b). Ignition and acceleration were successfully completed on one attempt to an altitude of 45,000 feet at a Mach number of 0.42. At 40,000 feet successful ignition and acceleration were attained at limiting Mach numbers from 0.33 to 0.52. The engine could not be ignited at 40,000 feet at a Mach number higher than 0.52.

The results indicate only small differences between the two ignition systems insofar as altitude ignition is concerned. In consideration of the absolute ignition limits shown for the J34-WE-32 engine in this investigation, the fuel temperature of 80° F must be recognized. Investigations discussed earlier in this paper indicate that cold fuel tends to lower the altitude ignition limits, although the limits of volatile fuels such as gasoline are lowered less than those for non-volatile fuels.

Effect of spark-plug location. - Fundamental investigations of the effect of environment on ease of ignition have shown that the energy required for igniting a homogeneous mixture of a gaseous fuel and air is dependent on the fuel-air ratio of the mixture. In an engine using a liquid fuel, a homogeneous mixture of vaporized fuel and air is not possible. Besides being stratified, most of the fuel will be in the liquid state and, therefore, may tend to quench rather than propagate a flame. Because of this fact and the fact that spark-plug electrodes

are often placed directly in line with the fuel emanating from the fuel nozzle, an investigation was conducted (unpublished NACA data) to study the influence of spark-electrode location on ignition limits by changing both the fuel-spray cone angle and the spark-electrode location. The best results, however, were obtained with the standard 120° spray cone angle for which the results are presented in figure 18.

The altitude ignition limits are shown for the J35-A-17 engine for each spark-plug location. As the spark plug immersion was increased, there was a rapid rise in the altitude at which ignition could be obtained. The greatest improvement was at the high flight Mach numbers where the altitude limit was increased from 10,000 to 35,000 feet.

These data indicate a greater accumulation of vapor fuels well inside the fuel spray cone and possibly less effect of quenching by the liquid fuel as idealistically shown in figure 19.

Fuel volatility. - One investigation of the influence of fuel volatility on altitude starting limits was conducted in flight on a J35-C-3a engine (reference 8). This engine was equipped with a J33 engine fuel control system. Windmilling starts were attempted with JP-3 (NACA fuel 48-210) fuel and JP-1 fuel.

The flight data were obtained by suspending the engine under a B-29 airplane and flying to a preselected altitude and Mach number. The fuel was put into the tanks at ground temperatures (not below 60° F) and flown to altitudes varying between 5000 and 30,000 feet. At the test altitude the turbine engine was allowed to windmill for at least 5 minutes before a start was attempted. After each successful start, at least 5 minutes elapsed before the second start was attempted. It can be assumed from this time schedule that at the time of a start the engine was cold and the inlet air was cold, but the fuel temperature was relatively high.

The results obtained in this investigation are shown in table III. All the data were determined at a flight Mach number of 0.37. The JP-1 fuel was started successfully at altitudes ranging from 5000 to 28,000 feet and the JP-3 fuel at altitudes between 6000 and 30,000 feet. Thus, it is shown that in this particular investigation in which the fuel used was relatively warm, both JP-1 and JP-3 fuels could be started successfully up to approximately 30,000 feet. It is of interest to note that the time required to accelerate the engine after the starts was greater in each case with JP-3 fuel. This fact will be discussed further in a later section of this report.

Additional starting tests (unpublished NACA data) indicate that the effect of fuel volatility becomes more pronounced when the fuel is cold as well as the engine and the inlet air. These results are shown in figure 20 for a J35-A-21 engine investigated in an altitude tank. Except at sea level and high flight Mach numbers the more volatile fuel (6.2-pound Reid vapor pressure (NACA fuel 50-246)) permitted starts to altitudes considerably higher than those found for the less volatile fuel (1-pound Reid vapor pressure (NACA fuel 50-197)).

The effects of fuel and air temperature on altitude ignition limits were determined in an altitude chamber with a J35-A-21 engine and a British Nene engine having the standard ignition systems installed (unpublished NACA data). The fuel used in the J35-A-21 engine had a Reid vapor pressure of 1.1 pounds per square inch (NACA fuel 49-246) whereas the fuel used in the Nene engine was a JP-1 type. Limits for the J35-A-21 engine were obtained at a flight Mach number of 0.6.

The change in altitude ignition limits of the J35-A-21 engine obtained by independently varying the fuel and air temperature is shown in figure 21. With a fuel temperature of 30° F, a reduction in inlet-air temperature from 10° to -50° F lowered the altitude ignition limit from 35,000 to 15,000 feet. With a fuel temperature of -30° F, no ignition could be obtained at any altitude with inlet temperatures below -15° F.

Additional runs were made with the J35-A-21 engine to determine the minimum fuel and air temperatures at which static sea-level starts could be made using the 1.1-pound Reid vapor pressure fuel. It was found that ignition could be readily obtained at temperatures as low as -50° F, the limit of the refrigeration system.

With the Nene engine it was found that reducing the fuel and air temperatures from a value between 60° and 90° F to 20° F had no effect on the ignition limits below a flight Mach number of about 0.2 (fig. 22). Above a flight Mach number of 0.25, the altitude ignition limits were as much as 6000 to 13,000 feet lower with the 20° inlet temperature.

Altitude starting limits for JP-1 and JP-3 fuels have also been evaluated in a J33-A-23 engine (reference 7 and unpublished NACA data). The physical properties of the two fuels are given in table I under NACA fuels 48-249 (JP-3) and 48-306 (JP-1). The J33-A-23 engine was mounted in an altitude chamber and both manual and automatic starts were attempted. The technique involved in starting with manual control was to set the inlet-air conditions to correspond to the altitude and Mach number desired and to allow these conditions to stabilize in the

altitude chamber. The ignition was then turned on and the throttle momentarily opened to about 1/2-open position and then returned to the idling position. The burst of fuel supplied by momentarily opening the throttle served to provide a good spray and returning the throttle to idling position permitted a comparatively cool start for the engine. If the engine did not start within 30 seconds, the throttle was closed and the engine purged by blowing air through the engine for approximately 5 minutes. Fuels were supplied to the engine at a temperature of about 60° F but owing to the fact that the conditions were stabilized in the altitude chamber before the ignition was attempted and 5 minutes were allowed between each attempted start, it is likely that the fuel temperatures were considerably lower than 60° F when the ignition actually occurred.

The results of this investigation are shown in figure 23 where altitude is plotted against Mach number for both manual starts and automatic starts. The JP-3 fuel could be ignited with manual starts at 25,000 feet at a Mach number of 0.30 and at 35,000 feet at Mach numbers from 0.4 to 0.85. Under the same conditions the JP-1 fuel could be ignited only to an altitude of 10,000 feet at a Mach number of 0.25 and at 20,000 feet at Mach numbers of 0.6 and 0.85. For manual starts, therefore, the JP-3 type fuel could be ignited at altitudes 15,000 feet higher than JP-1 type fuel. For automatic starts, however, the JP-3 fuel could be ignited only to 25,000 feet at Mach numbers of 0.6 and 0.85 and the JP-1 fuel could be ignited to 20,000 feet under the same conditions. Thus, it may be observed that with the automatic starts the JP-1 type fuel could be ignited to an altitude as high as could be obtained with manual starts. With the JP-3 fuel, however, the manual starts gave considerably higher altitude limits than the automatic starts. In fact, with automatic starts at a Mach number of 0.4, the JP-1 fuel could be started at altitudes 5000 feet above those possible with the JP-3.

The effect of fuel volatility on the altitude starting characteristics has also been investigated in a J47 D (RX-1) engine (unpublished NACA data). The engine configuration used for the investigation had redesigned combustors (opposite-polarity ignition system), a 32-inch-diameter tail pipe burner, and a variable-area exhaust nozzle. The redesigned combustors had 2-inch-diameter cross-fire tubes and the first six secondary air holes had baffles that extended inward to direct the air flow toward the central combustion zone. The investigations were conducted by first stabilizing the engine windmilling speed and then opening the throttle to the idle (10°) thrust selector position. If ignition was not obtained within 20 seconds after the circuit was closed, the attempt was termed "no ignition" and the procedure was repeated at another windmilling speed. During this part of the test, the fuel flow was scheduled by an integrated electronic control.

The results of this investigation are presented in figure 24. In figure 24(a) the data were obtained with a fuel having a Reid vapor pressure of 7 pounds per square inch (NACA fuel 50-108). The tests were conducted at an inlet-air temperature varying from 0 to -6° F with a fuel temperature of 70° F. The circular symbols show conditions where ignition could be obtained in all the combustors and the triangular symbols show conditions where no ignition could be obtained. The effect of Mach number is quite pronounced. At a Mach number of 0.44, the combustors could be ignited at an altitude of 50,000 feet. As the Mach number was increased, altitude ignition limits were reduced and ignition could not be obtained above an altitude of about 36,000 feet at Mach numbers ranging from 0.70 to 1.0. The results obtained with a 1-pound Reid vapor pressure fuel (NACA fuel 49-246) are shown in figure 24(b). In this case, the fuel could be ignited to an altitude of 49,000 feet at Mach numbers below 0.43. As Mach numbers increased, the ignition limit dropped very rapidly. This test was conducted with air temperatures varying from 30° F to -20° F, with the fuel temperature at 70° F. The results of the investigations for these two fuels are plotted in figure 24(c), as altitude against Mach number. It is shown that both fuels can be started equally well at Mach numbers below approximately 0.45. At higher Mach numbers, however, the JP-3, 7-pound Reid vapor pressure fuel can be started at higher altitudes than the 1-pound fuel. It must be noted that the fuel temperatures in this investigation were maintained at 70° F. Results shown in previous figures would indicate that at lower fuel temperatures there would probably be a greater difference in the altitude starting limits of these two fuels.

The results of ignition studies on full-scale engines conducted at the Lewis laboratory indicate that, in general, (1) with a low energy spark system a fuel with a volatility within the JP-3 range can be ignited more readily at high altitudes than a fuel with a Reid vapor pressure of 1 pound per square inch; (2) the differences in ignitability of fuels with 7-pound and 1-pound Reid vapor pressures are more pronounced at low temperatures; (3) altitude ignition limits of turbojet engines can be improved by use of extended spark electrodes and by use of higher spark energies; (4) successful ignition of a 1-pound Reid vapor pressure fuel has been accomplished in a J35-A-17 engine at a simulated altitude above 57,000 feet with spark energies of 3.2 and 4.7 joules. The fuel temperature during this investigation was maintained at approximately ambient temperature down to -50° F.

FLAME PROPAGATION

In the introduction it was pointed out that a complete start of an aircraft gas-turbine engine provided with tubular combustors involves three separate steps; namely, (1) ignition in the combustors provided with spark plugs, (2) propagation of the flame through cross-over tubes to all of the combustors, and (3) acceleration of the engine to operating speed. Starting engines with annular combustors, of course, does not involve flame propagation through cross-fire tubes, but otherwise the starting problems are similar for engines provided with either type of combustor.

Cross-fire-tube diameter. - The mechanism of flame propagation through cross-fire tubes has been postulated to be by one of two methods. After ignition in a combustor containing a spark plug, the pressure may be higher than in an unignited combustor, and the flame may be blown through the cross-fire tube into the adjacent combustors, which are then ignited. At the present time insufficient measurements have been completed to definitely establish the existence of a pressure differential between ignited and unignited combustors. The second mechanism that has been proposed requires that a combustible mixture exist in the cross-fire tube before flame will propagate through the tube. If it is necessary to provide a combustible mixture in a cross-fire tube before flame propagation will occur, then inflammability limits determined in tubes of various size should indicate trends to be expected with cross-fire tubes of various diameter. Such a study of inflammability limits is reported in reference 4 and some of the data are shown in figure 25 for propane-air mixtures.

The inflammability limit in inches of mercury is plotted against percent by volume of propane in air for tubes of various diameter. Flame will not propagate in a vertical tube ignited at the bottom at pressures below the lines defining the limits for each tube. The plots show that as the tube diameter is increased flame can be propagated at lower pressures. It is also shown that the optimum fuel-air mixture is somewhat richer than stoichiometric.

A cross-plot of the minimum propagation limits is shown in figure 26 to indicate the effect of tube diameter on the maximum altitude at which propagation could be expected from results of the investigation. With the optimum propane-air mixture, the altitude propagation limit increased from 23,000 to 57,500 feet when the tube diameter was enlarged from 0.71 to 2.0 inches.

Engine investigations in altitude facilities. - The limiting altitude for flame propagation through cross-fire tubes has been determined

in full-scale engines. The altitude limits for propagation in a J35-A-17 engine are shown in figure 27. The engine was provided with standard 7/8-inch-diameter cross-fire tubes and a JP-3 type fuel with 5.4 pounds Reid vapor pressure was used in the investigation. The limiting altitude at which propagation could be obtained is plotted against flight Mach number. It is shown that flame would propagate up to 45,000 feet at a Mach number of 0.25 and up to 35,000 feet at Mach numbers of 0.6 and 0.8.

The effect of cross-fire tube diameter on flame propagation has been studied briefly in a J47 engine (reference 11) with aviation-gasoline type fuel. The tube sizes were changed from the standard diameter of 1 inch to diameters of $1\frac{3}{16}$ and $1\frac{7}{16}$ inches. The effect of these changes on flame propagation was determined at a flight Mach number of 0.4. The results are shown in figure 28 as percentage of attempts for which satisfactory propagation was obtained plotted against altitude. It is shown that with 1-inch-diameter cross-fire tubes only 16 percent of the attempts gave successful propagation at 35,000 feet and propagation could not be obtained at 40,000 and 45,000 feet. The $1\frac{3}{16}$- inch cross-fire tubes gave improved propagation, and the $1\frac{7}{16}$ inch tubes gave successful propagation 80 to 100 percent of the attempts at altitudes from 35,000 to 45,000 feet. These data show that successful flame propagation is most likely to occur with cross-fire tubes of large diameter.

It is interesting to note that the results shown in figure 28 for a full-scale engine are in satisfactory agreement with results shown in figure 26 for upward propagation in vertical glass tubes.

Flight investigations. - The effect of the diameter of cross-fire tubes on flame propagation has been investigated in flight by the U.S. Air Force at Edwards Air Force Base (reference 17). An XB-43 airplane was used for the flights. The investigation was conducted on J35-A-9 engines provided with ignition plugs for J47 engines. One phase of the program was to determine the limiting altitude for satisfactory flame propagation with cross-fire tubes of 7/8-, $1\frac{5}{32}$-, $1\frac{15}{16}$-, $1\frac{25}{64}$-, and $1\frac{33}{64}$-inch diameter. The tests were conducted at a flight speed of 200 miles per hour with a JP-1 type fuel.

The limiting altitude for successful flame propagation was 30,000 feet with cross-fire tube diameters of 7/8- and $1\frac{5}{32}$-inch diameters. The larger cross-fire tubes gave successful flame propagation

at 40,000 feet. These results reemphasize the importance of cross-fire tubes of suitable diameter for successful flame propagation at high altitudes.

Effect of Fuel Volatility on Flame Propagation

The effect of fuel volatility on flame propagation through cross-fire tubes has been investigated at the Lewis laboratory on a J35-A-17 engine. Flame propagation limits were obtained with a JP-3 type fuel with a Reid vapor pressure of 5.4 pounds per square inch (NACA fuel 48-249) and compared with a fuel with a Reid vapor pressure of 1.1 pounds per square inch (NACA fuel 49-246). The propagation limits of the two fuels are shown in figure 29 where limiting altitude is plotted against flight Mach number. The fuel with the 5.4-pound Reid vapor pressure gave propagation limits from 5000 to 7500 feet higher than limits obtained with the 1.1-pound Reid vapor pressure fuel.

It is of importance to know whether ignition or flame propagation may be establishing the altitude starting limit of an engine. Comparison of figures 20 and 29 shows that with the 1.1-pound Reid vapor pressure fuel the ignition limit and propagation limits were the same from a Mach number of 0.2 to 0.4. Above 0.4 the ignition limit was lower than the propagation limit so that ignition was establishing the limiting altitude. The higher volatility fuels at a Mach number of 0.4 gave ignition 5000 feet above the propagation limit, but at higher Mach numbers the ignition limit was lower than the propagation limit. Thus, in this particular study, the ignition process seemed to be limiting more frequently than the propagation. This statement is not necessarily true of other engines. The above comparison is made for a J35-A-17 and a J35-A-23 engine, which have the same type combustors.

Summary of Flame Propagation Data

In summarizing the relatively meager data on flame propagation, two points may be made: (1) Enlarging the diameter of cross-fire tubes improves flame propagation at high altitudes; tube diameters of $1\frac{7}{16}$-inches or greater are indicated. (2) In one investigation, a fuel with a Reid vapor pressure of 5.4 pounds per square inch gave flame propagation limits 5000 to 7500 feet higher than propagation limits obtained with a fuel with a Reid vapor pressure of 1.1 pounds per square inch.

ACCELERATION

It was previously mentioned that ignition, flame propagation, or acceleration can establish the maximum altitude at which successful starts can be accomplished. Some of the pertinent data on acceleration are presented.

The time required to accelerate a J47 engine at various altitudes is shown in figure 30. The time required to accelerate the engine is plotted against percent of rated engine speed. The data are presented for several altitudes at a constant flight Mach number of 0.30. It is shown that the time required for acceleration is markedly increased as altitude is increased.

At an altitude of 15,000 feet, an acceleration from 76-percent rated speed to 100-percent rated speed required 6 seconds; whereas at 45,000 feet the time required for the same acceleration was 40 seconds. The accelerations at 15,000 and 25,000 feet were made by rapid advances of the throttle to the full-open position, with the time for acceleration governed by the engine control system. Both accelerations were made at the same turbine-outlet temperature. Above an altitude of about 30,000 feet it was necessary to control all the accelerations manually, because rapid throttle advances often caused compressor stall.

At altitudes above 35,000 feet rapid throttle advances usually caused combustion blow-out. The combustion blow-out problem became more difficult as the altitude was increased and at 45,000 feet it was necessary to accelerate with exhaust-gas temperatures 200° to 300° F lower than at 25,000 feet. Careful manipulation of the throttle at 45,000 feet caused the irregularities in the curve shown in figure 30.

Consideration of the problem of acceleration indicates that at high altitudes it will necessarily require a longer time to accelerate a turbine engine than at low altitudes, because the mass of the rotating engine parts is constant but the flow of air through the engine is reduced as altitude is increased. Predictions of acceleration time can be made on the basis that the ratio of time required to accelerate at a given altitude to the time required to accelerate at sea-level varies approximately as the inverse of the ambient-air density. On this basis the time for acceleration of a J47 engine has been calculated for various altitudes. The calculations are compared with actual accelerations of the same engine in figure 31 where acceleration time is plotted against altitude. The experimentally determined time for acceleration at 15,000 feet was taken as the base point for the predicted curve. The experimental and predicted curves agree up to an

altitude of 25,000 feet. At higher altitudes, however, the actual time for acceleration is longer than the calculated value. At altitudes between 25,000 and about 35,000 feet, the additional time is required in order to avoid compressor stall. At these altitudes the compressor would stall if the gas temperatures at the turbine inlet were allowed to go to the limiting values set by materials considerations. Gas temperatures were therefore held somewhat below the limiting allowable values and, consequently, the times required for acceleration were longer than the predicted times. At altitudes between 35,000 and 45,000 feet, combustion blow-out was encountered before maximum gas temperatures could be attained. In order to avoid combustion blow-out, gas temperatures at the turbine position were therefore maintained lower than allowable from materials considerations and, consequently, the experimentally determined acceleration times were greater than those predicted. The results shown in figure 31 are considered typical of the experience at the Lewis laboratory on full-scale engines.

Another phenomenon that contributes to slow accelerations on some engines is the flame burning downstream of the turbine. In some cases enough fuel burns downstream of the turbine so that the turbine outlet pressure is raised and the pressure drop across the turbine is less than normal, and thus the power available for acceleration is less than predicted. This phenomenon is often encountered in turbojet engines at high altitudes and low flight Mach numbers.

The time required to accelerate a gas-turbine engine can be reduced by increasing the air flow through the engine and by increasing the pressure ratio across the turbine. These can be attained to a certain extent by increasing flight Mach number. The effect of flight Mach number on acceleration time is shown in figure 32, where acceleration time is plotted against percent of rated engine speed. The data were obtained on a J47 engine at a simulated altitude of 40,000 feet at flight Mach numbers of 0.37, 0.57, and 0.62. At a Mach number of 0.37 the engine was accelerated from 76-percent to 97-percent rated speed in 22 seconds. At a Mach number of 0.62 only 9 seconds were required. A part of this reduction in time for acceleration resulted from being able to utilize slightly higher exhaust-gas temperatures as flight Mach number was increased, without encountering combustion blow-out. This is an additional gain, which will vary from one engine type to another, over the gains in air flow and pressure ratio attributed to higher Mach numbers.

In addition to increasing the pressure ratio across the turbine by increasing flight Mach number, the pressure ratio can be increased by increasing the exhaust-nozzle area by use of a variable-area nozzle.

An increase in nozzle area causes a reduction in turbine-outlet pressure, which provides increased power for acceleration and tends to alleviate the condition of compressor stall. The effect of a 50-percent increase in exhaust-nozzle area on the acceleration time of a J47 turbojet engine, from windmilling starting speed to rated speed, at a Mach number of 0.4, is shown in figure 33; where acceleration time is plotted against altitude. At 35,000 feet the acceleration time with the standard jet nozzle was 130 seconds and at 45,000 feet the acceleration time was 255 seconds. When the exhaust-nozzle area was increased by 50 percent, the acceleration time at 35,000 feet was reduced by 50 percent and the acceleration time at 45,000 feet was reduced by 35 percent. Thus, it is shown that a variable-area exhaust nozzle greatly reduces acceleration time; but acceleration times at high altitudes are still very long.

The limiting altitude at which acceleration could be obtained has been determined for the J35-A-17 engine with JP-3 type fuel. The data are presented in figure 34 as a plot of altitude against flight Mach number. It is shown that the engine could not be accelerated up to an altitude of 20,000 feet at a Mach number of 0.25. At a Mach number of 0.6 the engine could be accelerated up to an altitude of 35,000 feet.

At the present time there are very few data to show the effect of fuels on acceleration time or on the absolute altitude limits for accelerations. However, there are a few indications of the effect of fuel volatility as shown by the performance of JP-1 and JP-3 fuels in a J35-C3A engine (table III). Accelerations were obtained with both fuels at four different altitudes up to about 30,000 feet, and in every case shorter acceleration times were obtained with the JP-1 fuel. Thus, the less volatile fuel gave the better acceleration characteristics.

The results indicate the possibility that under marginal operating conditions a volatile fuel creates fuel-rich mixtures near the fuel nozzles. After the fuel vapors travel downstream in the combustor, they form combustible mixtures but there is insufficient time for complete heat release before the gases are swept through the turbine. A nonvolatile fuel forms vapor less rapidly and may not form zones too rich to burn, and may provide greater heat release than a volatile fuel. This concept is consistent with the results of combustor investigations of altitude operational limits with fuels of various volatilities (reference 18). The idea also seems consistent with results of accelerations conducted with a J47 engine in the altitude wind tunnel (reference 11). It was found that at 250 miles per hour at altitudes of 40,000 and 45,000 feet, the engine could not be accelerated with the standard fuel system because of combustion blow-out. The engine could

be accelerated at the same condition with a fuel system that distributed fuel uniformly to all combustors and provided larger fuel droplets to the combustors than provided by the standard fuel system. It seems likely that large fuel droplets evaporate slowly and act like a non-volatile fuel in accelerating the engine.

These data along with information to be presented in the next section indicate that use of a 1-pound Reid vapor pressure fuel in place of a 7-pound Reid vapor pressure fuel would not increase the acceleration problem of turbojet engines provided with tubular combustors.

After consideration of ignition, propagation, and acceleration separately, it is of interest to determine which of the three processes establishes the altitude starting limit for an engine. Such data are shown in figure 35 for a J35-A-17 engine with JP-3 type fuel. The investigation was conducted in an altitude facility. Altitude is plotted against Mach number and the three lines define limiting altitudes for ignition, flame propagation, and acceleration. In the original engine, ignition could be obtained up to 50,000 feet at a Mach number of 0.25 but fell rapidly as the Mach number was increased. After the ignition limit had been raised by the use of extended spark electrodes, the propagation and acceleration limits were determined. It is shown that up to a Mach number of 0.5 the acceleration limit established the altitude starting limit of the engine. Above a Mach number of 0.5 the ignition was the limiting factor.

The limits set by ignition, propagation, and accleration would be expected to vary with other engine-fuel combinations.

FLIGHT INVESTIGATIONS OF COMPLETE STARTS

Flight investigations have been conducted by the U.S. Air Force at Edwards Air Force Base to determine the effect of fuel volatility on altitude starting. The results of these investigations have been reported orally to the NACA.

The experiments were conducted in an F-80 airplane with a J33-A-23 engine modified with a low-pressure fuel system of the type used in the J33-A-35 engine. In addition, the standard size cross-fire tubes were replaced with tubes of larger diameter.

The fuels investigated included a JP-1, a JP-3 type, and a 1-pound Reid vapor pressure type. The fuel temperatures were estimated to be about 60° F.

The starting procedure involved flying to a high altitude, shutting off the engine; then turning on the ignition after one minute and turning on the fuel after another minute. The starts were conducted with automatic controls. The airplane lost altitude at the rate of about 3000 feet in 2 minutes. Indicated air speed was about 225 miles per hour when starts were attempted.

The experiments with JP-1 type fuel indicated no starts or poor starts at 20,000 feet and higher. This limiting altitude is the same as the ignition limit established in an altitude chamber with an unmodified J33-A-23 engine and a JP-1 fuel (reference 7).

The flight tests with the JP-3 type fuel indicated good starts up to an altitude of 35,000 feet. At altitudes between 35,000 and 40,000 feet the engine sometimes started but always with considerable delay and with excessive turbine temperatures.

The flight tests with the 1-pound Reid vapor pressure fuel showed three successful starts at 40,000 feet. In another attempt, the engine failed to start at 40,000 feet but started successfully three times at 37,500 feet.

Comparison of the results obtained with the JP-3 type fuel and the 1-pound Reid vapor pressure fuel indicated that the volatile JP-3 was easier to start than the 1-pound fuel up to an altitude of 35,000 feet. Above 35,000 feet the 1-pound fuel gave better starts than the JP-3 fuel. This result may be due to formation of excessively rich mixtures with the JP-3 as previously discussed.

Starting tests have also been conducted by the Bureau of Aeronautics, Navy Department. One of the studies has been reported orally to the NACA and shows the importance of spark energy on starting, and the role that acceleration plays in establishing the starting limits of an engine.

Flight tests were conducted at Pautexant River with an F-2H2 airplane provided with a J34-W-34 engine. Starting tests were conducted with a standard ignition system and with a special intermittent-duty, low-voltage high-energy ignition system employing surface-gap spark plugs. The system was designated TLN-2 Bendix with modified (1-10411-1) plugs. The fuel was a JP-3 type at an estimated temperature of 60° F.

Successful starts were made with the standard ignition system to an altitude of about 30,000 feet. The high-energy ignition system gave successful starts up to 41,000 feet. The high-energy system would

ignite the engine up to an altitude of 44,000 feet but the engine could not be accelerated above an altitude of 41,000 feet. It was reported that the unsuccessful accelerations were due to both compressor stall and combustion blow-out.

This investigation shows quite clearly the advantage of a high-energy ignition system and reemphasizes the acceleration problem.

CONCLUDING REMARKS

An attempt has been made in this report to summarize the available information on the starting of gas-turbine engines. Starting has been considered as three phases; namely, (1) ignition of the fuel-air mixture in the combustor, (2) propagation of flame through cross-fire tubes to all combustors, and (3) acceleration of the engine from windmilling or starting speed to the normal operating speed. Certain comments can be made about each phase of the starting process.

Some of the current turbojet engines seem to be provided with insufficient spark energy to allow reliable ignition at high altitude conditions and high flight Mach numbers, even with an optimum fuel.

Engines with low-energy ignition systems can be more satisfactorily ignited at high altitudes with a 7-pound Reid vapor pressure fuel than with a 1-pound Reid vapor pressure fuel. The differences in the ignition limits of the two fuels are most pronounced when the fuels are cold.

Data from one single-combustor investigation and one full-scale engine investigation indicate that spark energies from about 4 to 10 joules will ignite both 1-pound fuels and 7-pound fuels at altitudes of 50,000 to 60,000 feet.

Spark electrodes that extend well into the combustor provide improved ignition in tubular combustors.

Flame propagation through cross-fire tubes can be improved at high altitudes by increasing the diameter of the tubes. Present investigations indicate that tube diameters of at least 2 inches should be used.

One investigation has shown that a 7-pound Reid vapor pressure fuel will allow flame propagation at altitudes 5000 to 7500 feet higher than a 1-pound fuel.

The time required to accelerate turbojet engines at moderate and high altitudes is expected to be longer than at low altitudes, because of reduced air density at altitude. The adverse effect of altitude on acceleration can be greatly reduced by use of a variable-area exhaust nozzle.

Acceleration times, however, even with variable-area exhaust nozzles, are longer than predicted on the basis of air density, because of compressor stall and combustion blow-out.

The meager information on the effect of fuel volatility on engine acceleration at high altitudes indicates that a 1-pound fuel and a 7-pound fuel will probably give approximately equal performance.

The information available on complete engine starts - that is, ignition, propagation, and acceleration - indicates the need for a comparison of 7-pound and 1-pound Reid vapor pressure fuel at high altitudes with both fuels maintained at low temperatures.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, January 31, 1951.

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TABLE I - FUEL INSPECTION DATA

	80-Octane clear gasoline	JP-3 Types							JP-1	Experimental		
NACA fuel	50-237	50-174	49-245	48-210	50-246	48-249	50-108	49-162	48-306	49-246	50-197[c]	49-170[d]
A.S.T.M. distillation D 86-46, °F												
Initial boiling point	112	114	99	102	124	110	100	109	336	210	181	120
Percentage evaporated												
5	140	128	113	149	156	135	119	135	349	224	242	153
10	159	138	128	174	180	157	140	158	355	243	271	170
20	183	149	148	234	220	198	192	210	360	276	300	184
30	203	160	187	286	252	230	274	270	365	302	319	200
40	216	174	243	322	282	272	327	323	370	328	332	206
50	229	188	292	360	312	314	353	360	375	355	351	210
60	242	204	334	390	344	351	374	398	381	384	365	219
70	255	231	374	412	378	388	393	432	387	413	381	224
80	270	330	416	444	408	427	427	460	394	441	403	230
90	296	439	463	480	447	473	490	500	405	478	441	243
Final boiling point	346	533	548	545	498	560	611	584	446	560	508	333
Residue, (percent)	1.0	1.0	1.0	0.8	1.0	1.0	2.2	1.0	1.0	1.0	1.0	0.7
Loss, (percent)	1.0	1.0	1.5	0.2	0.5	1.0	0.8	1.0	1.0	1.0	0.5	1.3
Freezing point, (°F)	------	-72	-76	-76	-76	-76	------	-76	-76	-76	-76	-76
Accelerated gum (mg/100 ml)	------	------	7	------	------	2.9	------	16	0	------	5	-------
Air-jet residue (mg/100 ml)	------	------	2	20	------	3	------	8	1	------	2	-------
Sulfur, (percent by weight)	------	------	0.50	0.09	------	0.03	------	0.50	0.02	------	-------	-------
Aromatics, (percent by volume)												
D 875-46 T	------	------	15	23	------	17	------	25	15	------	-------	-------
Silica gel[a]	------	5.7	[b]17	29	------	19	------	[b]31	15	23.5	5.70	9.0
Specific gravity	0.721	0.725	0.757	0.794	0.760	0.769	0.762	0.801	0.831	0.803	0.780	0.718
Viscosity, (centistokes at -40° F)	------	1.65	2.4	4.26	------	2.67	------	4.1	9.2	4.28	-------	-------
Bromine number	------	0.9	12	12	------	13.8	------	12	0	7	1.4	-------
Reid vapor pressure, (lb/sq in.)	6.3	6.5	7.0	5.7	6.2	5.4	6.8	4.5	------	1.1	1.0	4.2
Hydrogen-carbon ratio	0.177	0.172	[b]0.167	0.153	0.171	0.163	0.169	[b]0.150	0.154	0.157	0.170	0.182
Net heat of combustion, (Btu/lb)	18,850	18,800	[b]18,700	18,475	18,724	18,640	18,740	18,500	18,530	18,560	18,691	18,950

[a]Determined by method of reference 19.
[b]Calculated from base stock data.
[c]Supplied by Air Materiel Command, U.S. Air Force.
[d]Supplied by Air Materiel Command, U.S. Air Force. 115/145 grade weathered gasoline.

TABLE II - ENGINE STARTING CONFIGURATION AND OPERATIONAL DATA

Engine	Ignition system	Spark plugs	Fuel nozzles	Throttle control	Inlet-air temperature (°F)	Fuel temperature (°F)	Fuels[a] (NACA designation)
J33-A-23	Standard	Standard	Standard (Simplex; 75° cone angle)	Manual and automatic	Standard NACA to limit of -20	Equal to inlet-air temperature	48-249 48-306
British Nene II	Standard (12,000 v)	Torch igniter	Standard (Duplex)	Automatic	60-90 20	Equal to inlet-air temperature	48-306
J35-A-17	Standard (15,000 v)	Various	Standard (Duplex; 120° cone angle)	Manual	Standard NACA to limit of -20	Equal to inlet-air temperature	48-249 49-246
J35-A-21	Standard (15,000 v)	Standard and opposed electrode	Standard (Duplex; 120° cone angle)	Manual	Standard NACA to limit of -40 and cold-weather starts	Equal to inlet-air temperature	50-246 50-197
J47B-7	Various (20,000-40,000 v)	Various	Standard (Duplex; 50° to 70° cone angle)	Manual and automatic	-40	70-80	49-170
J47D(RX1)	Standard	Standard (opposed electrode)	Standard (Duplex; 50° to 70° cone angle)	Automatic	0 to 6 30 to -20	70	50-246 50-197
XJ34-WE-32	Standard	Standard	Standard (Simplex; 80° cone angle)	Automatic	15	80	50-237
J34-WE-22	Standard	Standard; extended electrode type	Standard	Manual	-30 to -50	70	48-210
J35-C-3a	Standard	Standard	Standard	Automatic	Ambient at designated altitude	Estimated to be 60	48-210 48-306

[a]See table I for physical properties.

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TABLE III - WINDMILLING STARTING AND ACCELERATION FLIGHT DATA FOR A J35-C-3a ENGINE

[Flight Mach number, 0.37]

Altitude (ft)	Wind-milling speed (rpm)	Free-air temperature (°F)	Successful start and acceleration	Maximum tail-pipe temperature (°F)	Acceleration	
					Time (sec)	Engine speed (rpm)
JP-1 Fuel						
5,000	1320	50	Yes	1150	36	6930
10,000	1280	47	----do.----	1140	61	6970
20,000	1300	15	----do.----	1300	68	7000
28,000	1130	-22	----do.----	1310	106	6930
JP-3 Fuel						
6,000	1300	44	----do.----	950	91	6780
10,000	1270	33	----do.----	810	74	[a]4940
20,000	1160	2	----do.----	1400	80	6990
30,000	1040	-38	----do.----	1380	153	6680

[a]No data obtained above 4940 rpm.

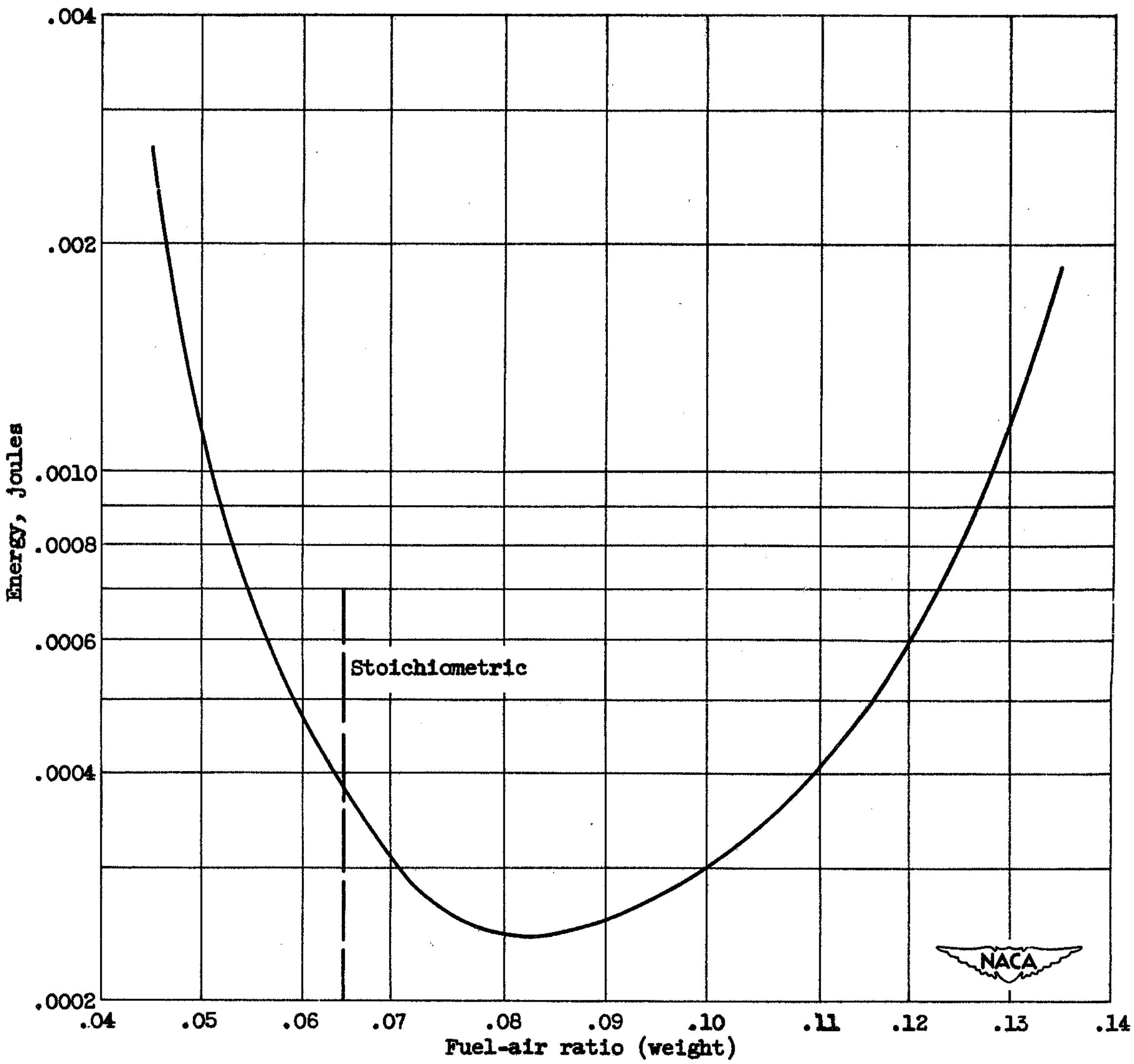

Figure 1. - Effect of fuel-air ratio on ignition energy of quiescent mixtures. Fuel, propane; optimum spark gap; pressure, 1 atmosphere.

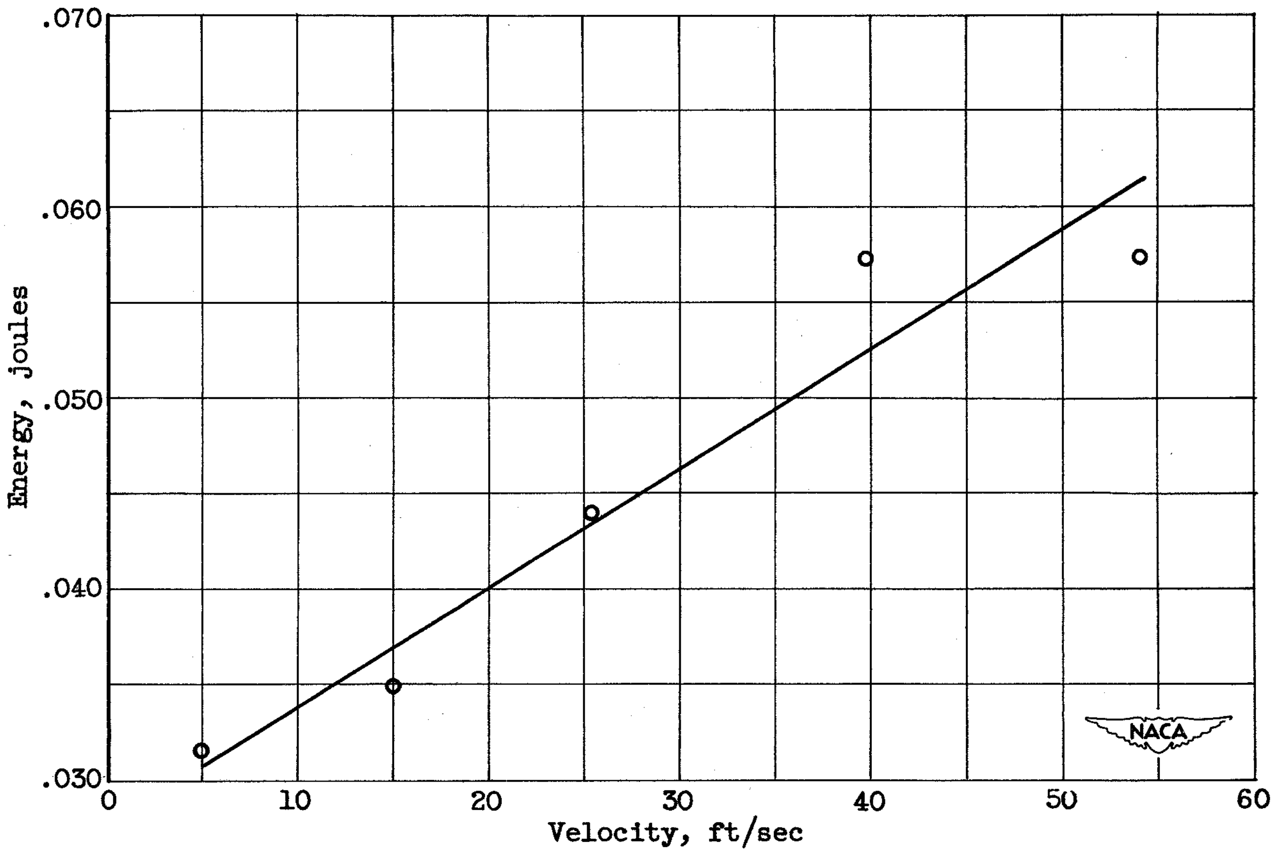

Figure 2. - Effect of velocity on energy required for ignition. Fuel, propane; fuel-air ratio, 0.055 by volume; electrode spacing, 0.25 inch; pressure, 0.1 atmosphere.

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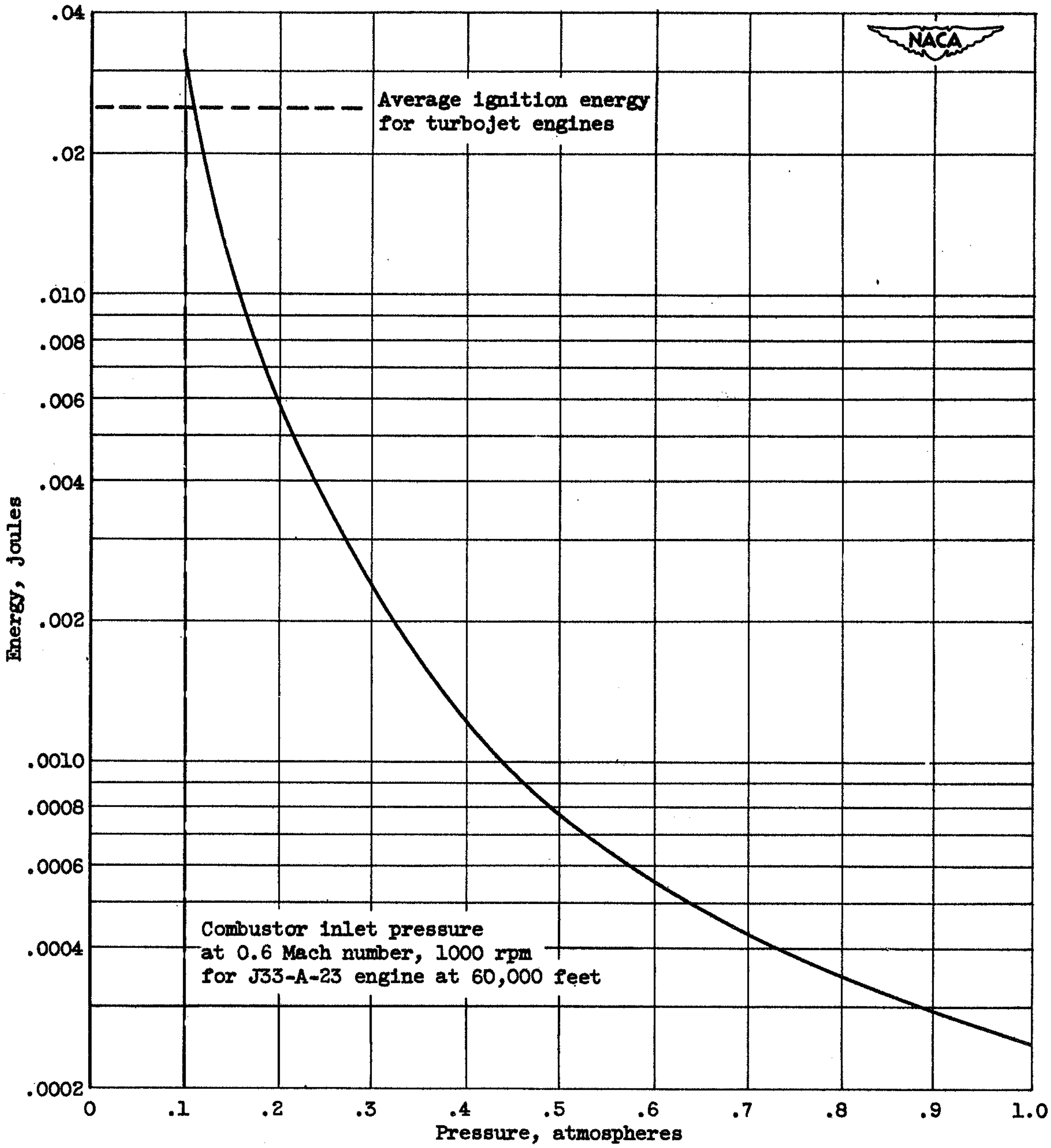

Figure 3. - Effect of pressure on energy required for ignition with propane-air mixture; optimum fuel-air ratio; optimum electrode spacing.

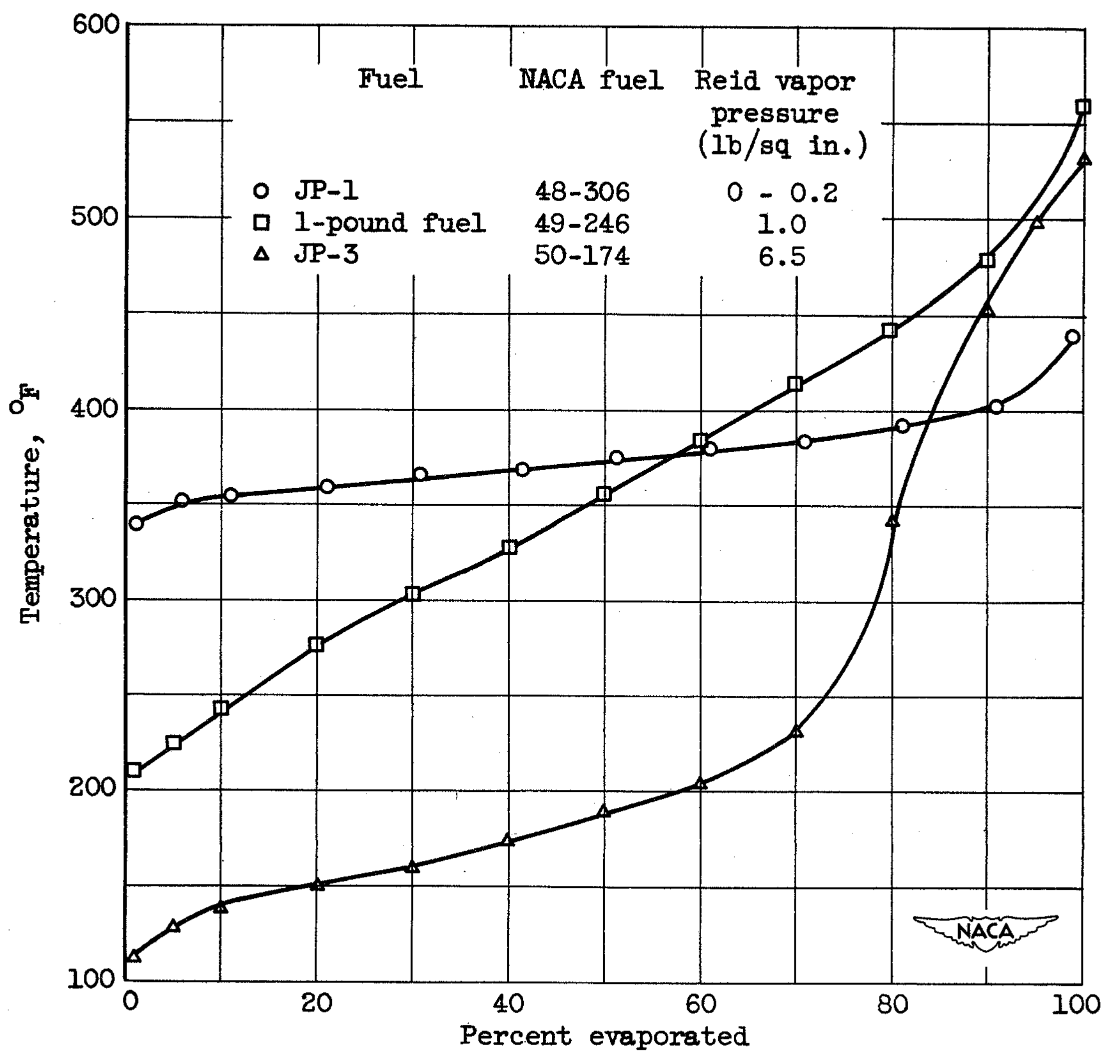

Figure 4. - Variation of distillation temperature with percentage evaporated for three fuels.

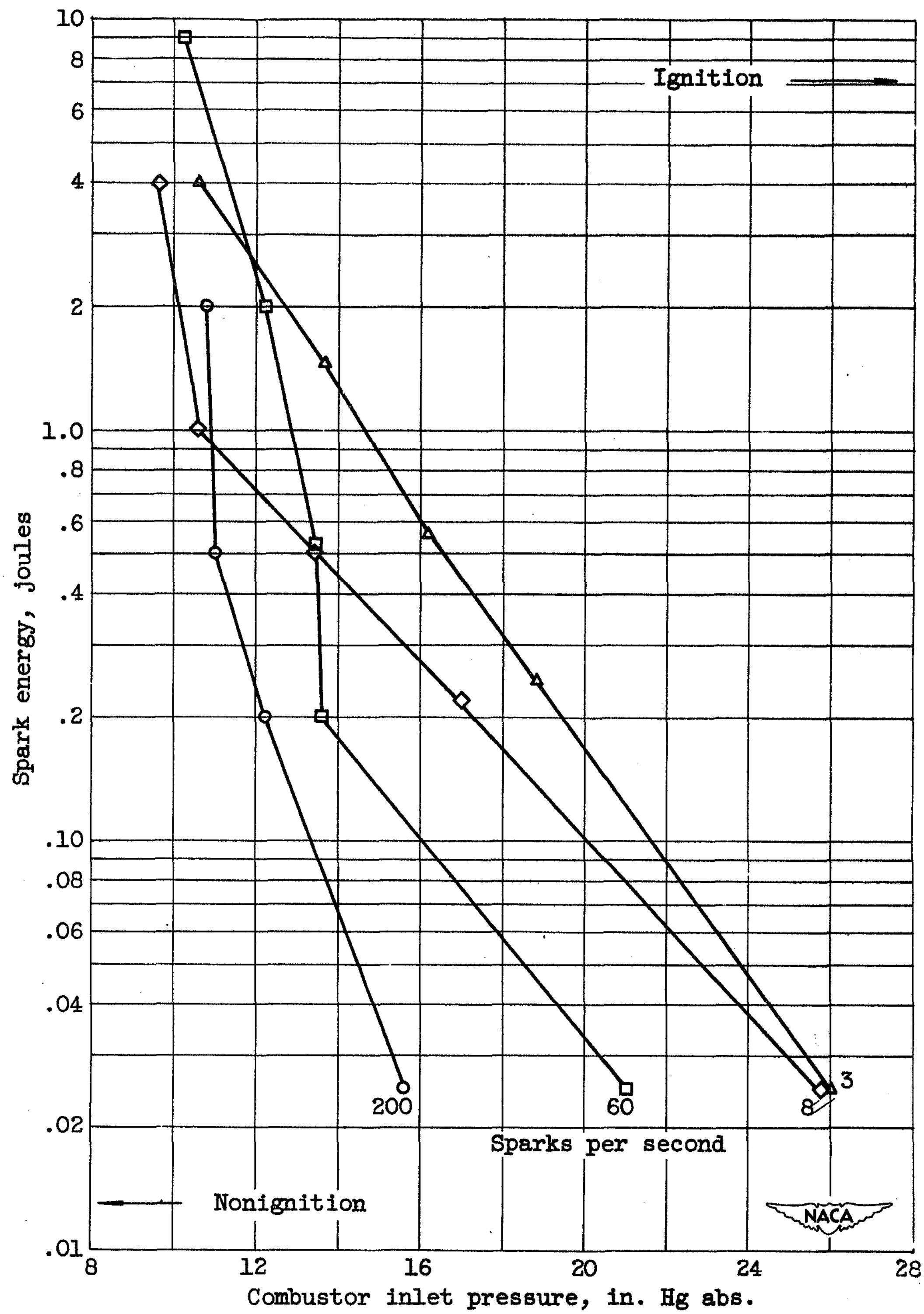

Figure 5. - Effect of spark rate, 0.1 ignition of J33 single combustor. One-pound fuel; air flow, 0.5 pound per second.

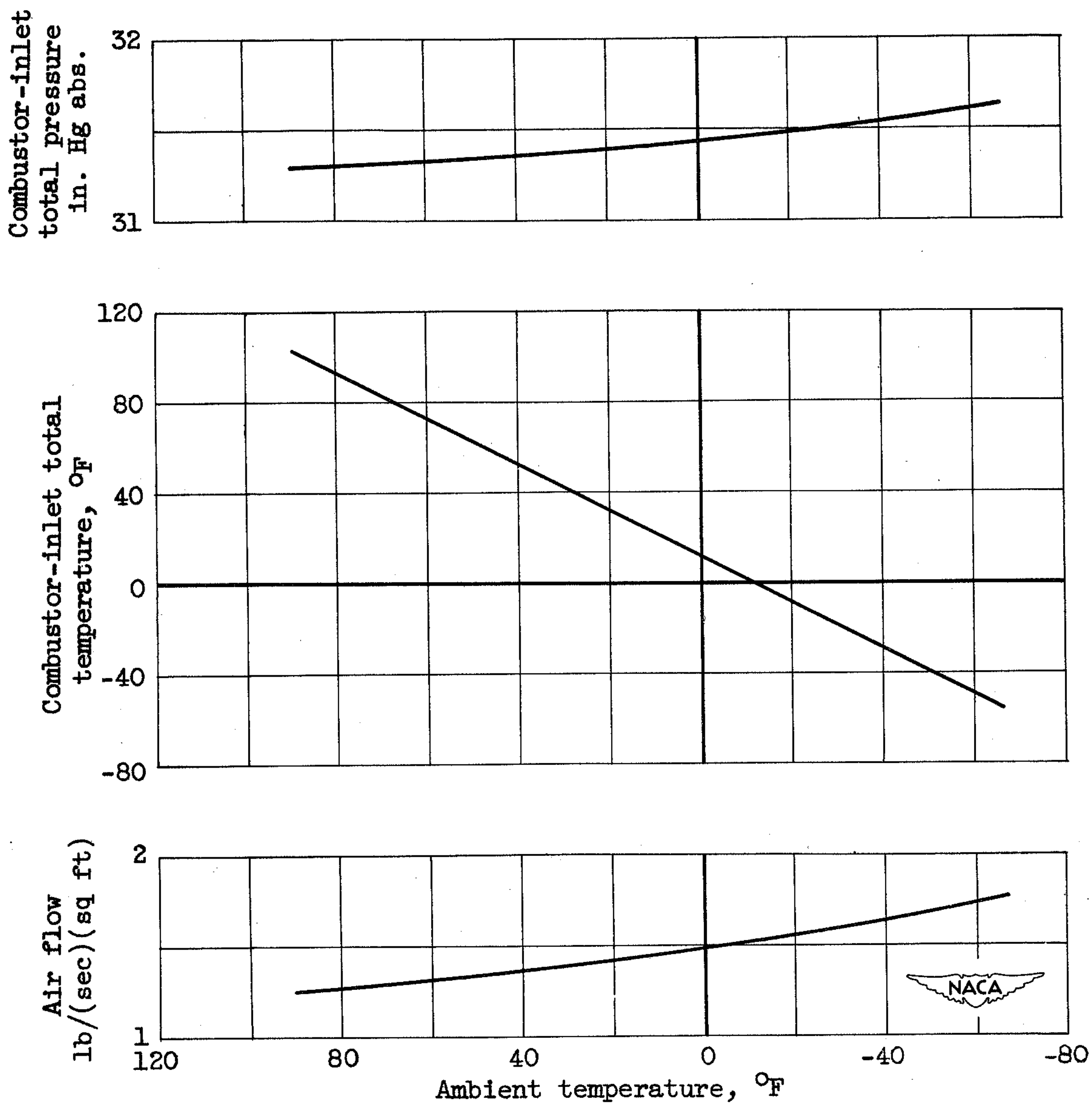

Figure 6. - Variation of air-flow parameters for J33 single combustor. Simulated engine speed, 9-percent normal rated rpm; static sea-level conditions.

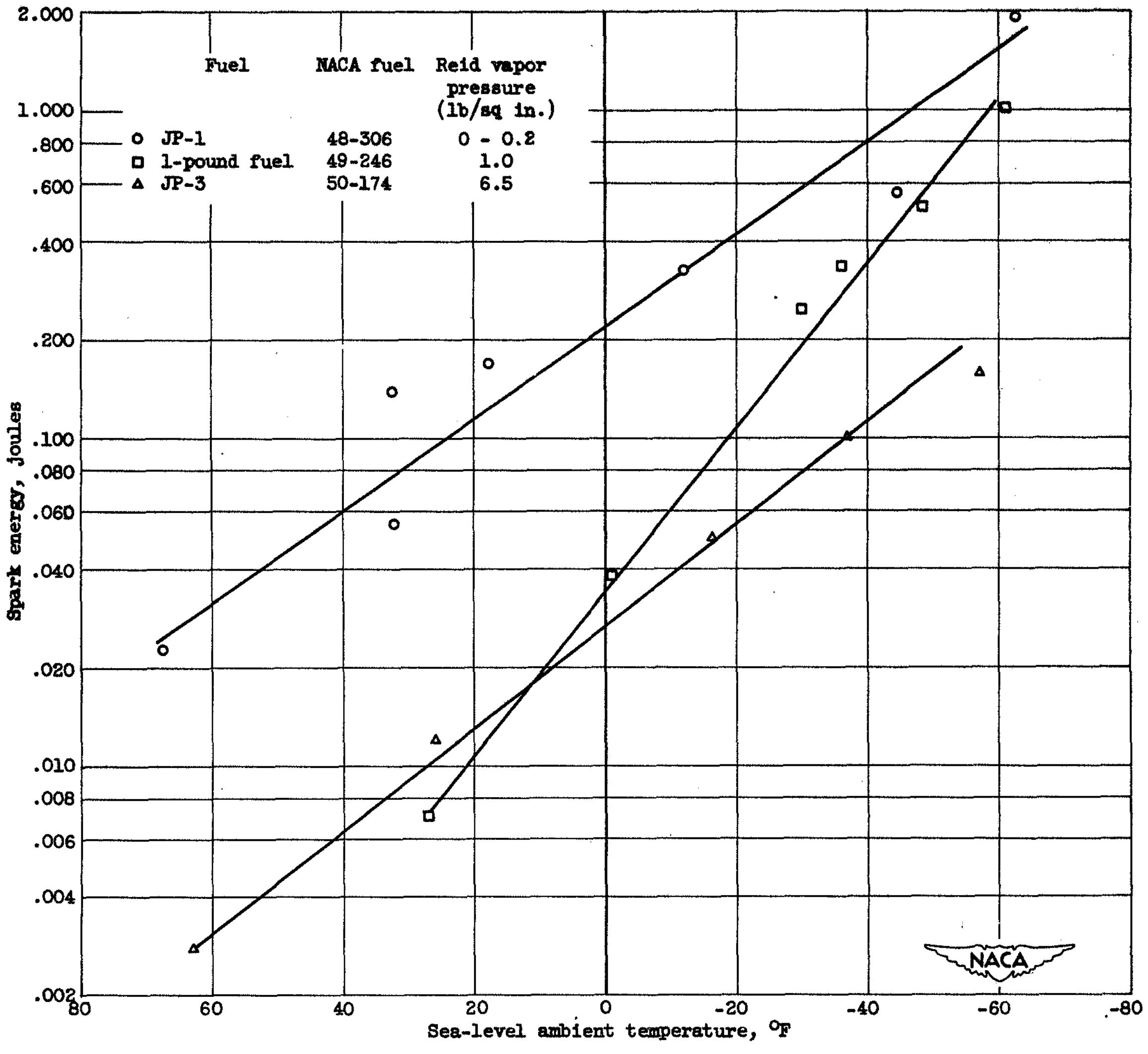

Figure 7. - Effect of sea-level ambient temperature on ignition of three fuels of different volatility at simulated engine cranking speed of 9-percent normal rated rpm in J33 single combustor.

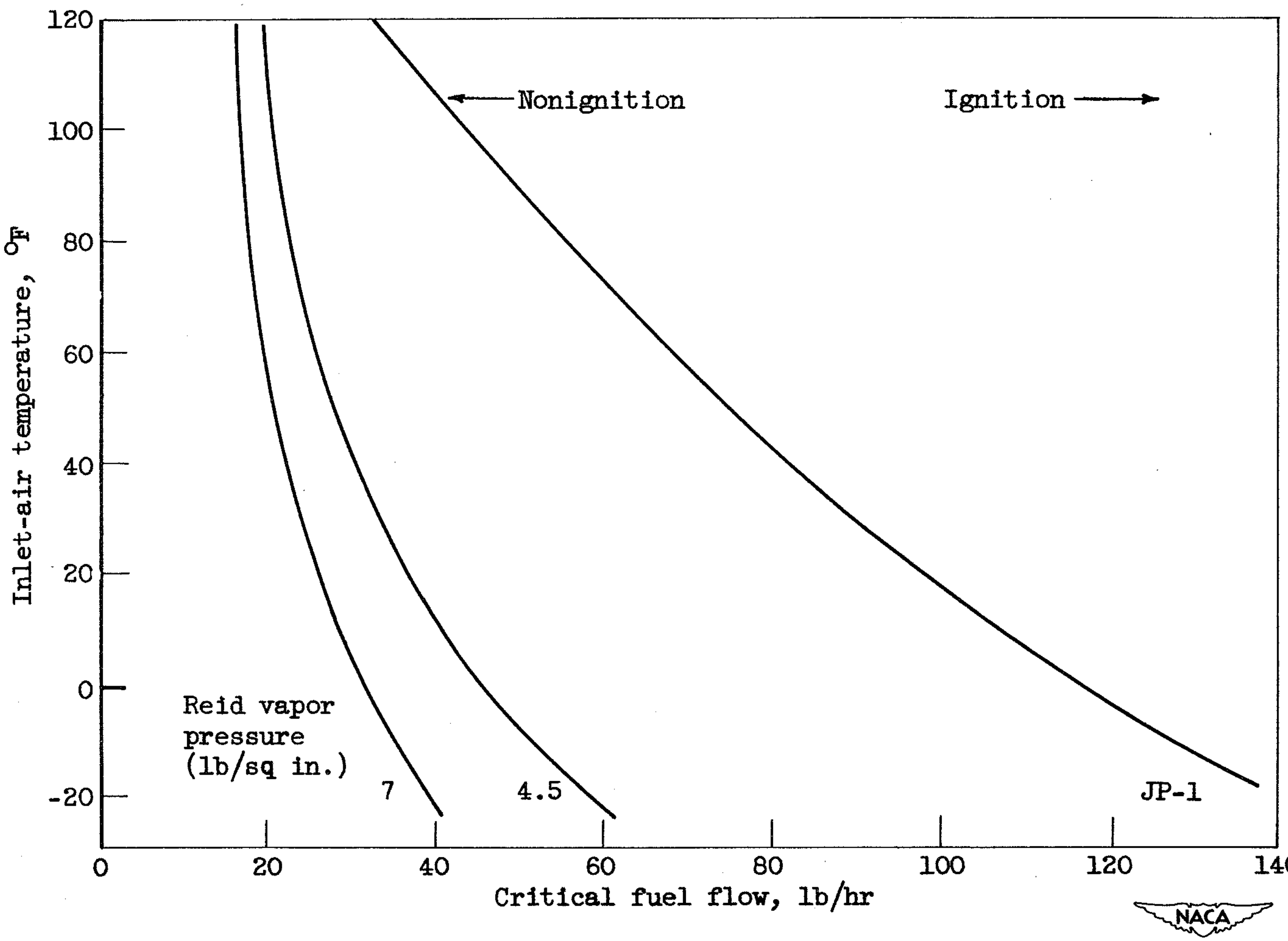

Figure 8. - Effect of temperature on fuel flow required for ignition in J33 single combustor. Engine speed, 1600 rpm; Mach number, 0; sea level; spark energy, 0.015 joule; rate, 60 per second.

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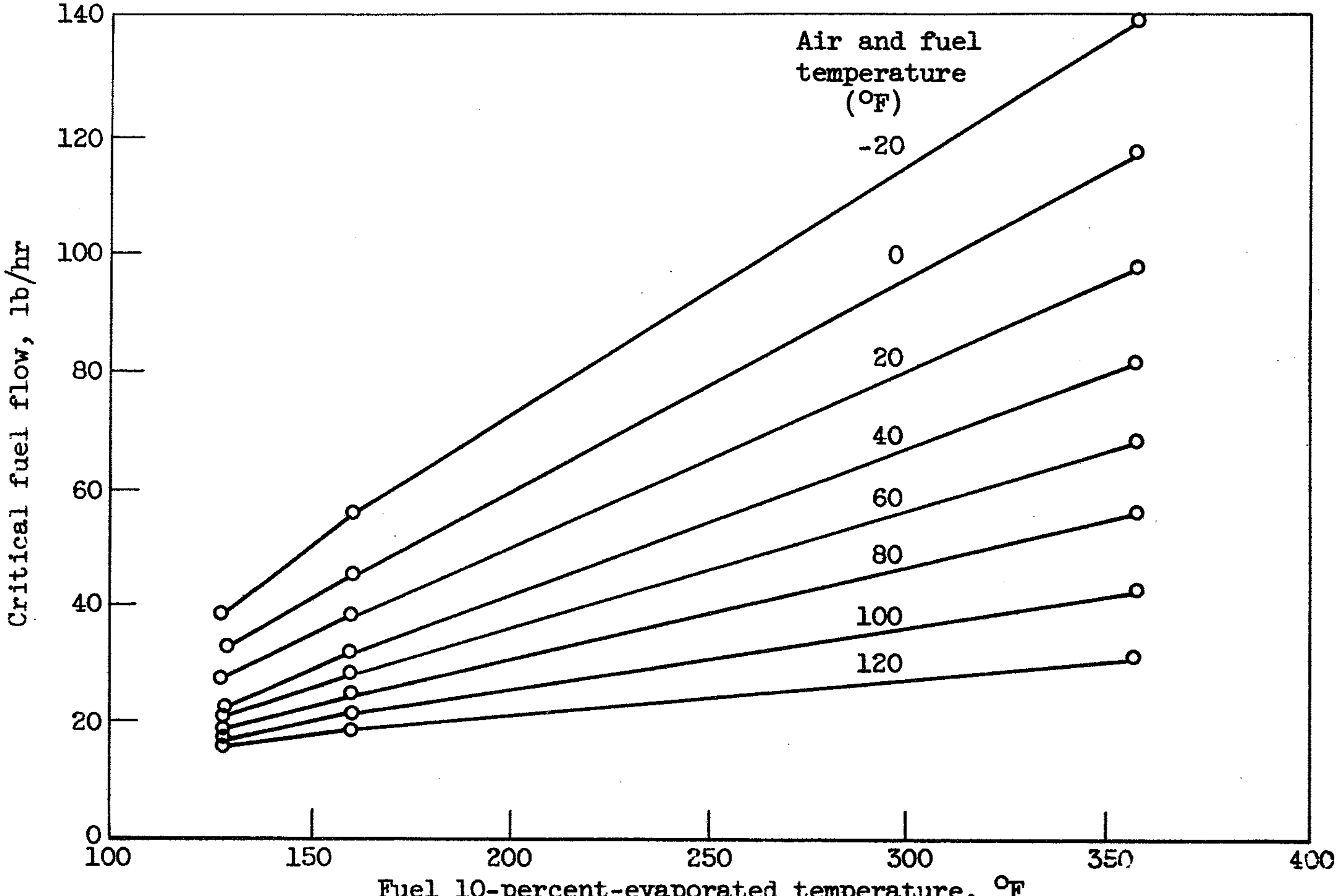


Figure 9. - Fuel flow required for ignition in J33 single combustor. Engine speed, 1600 rpm; Mach number, 0; sea level.

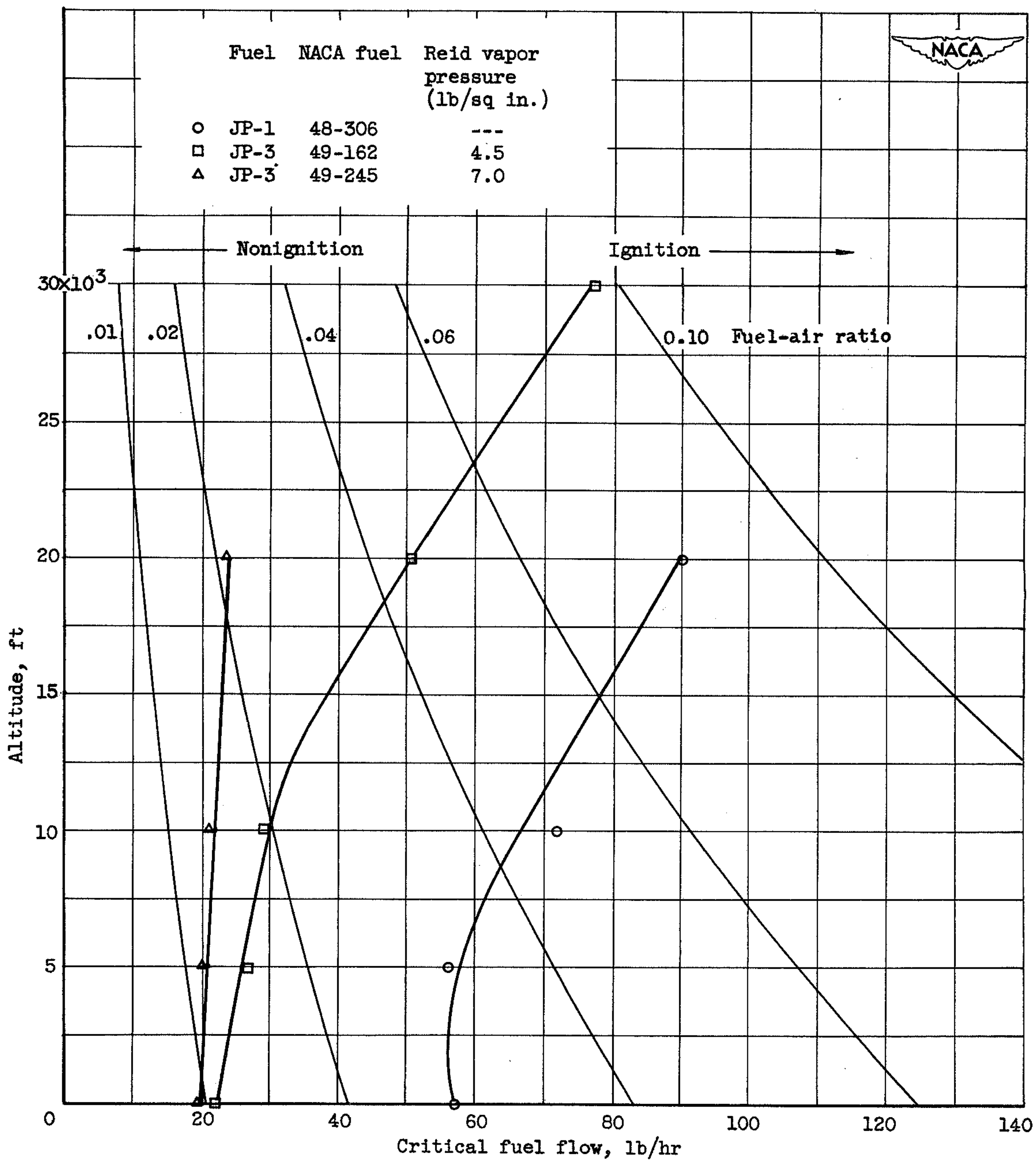


Figure 10. - Critical fuel flow for ignition for three fuels. Engine speed, 1600 rpm; flight Mach number, 0; J33 single combustor.

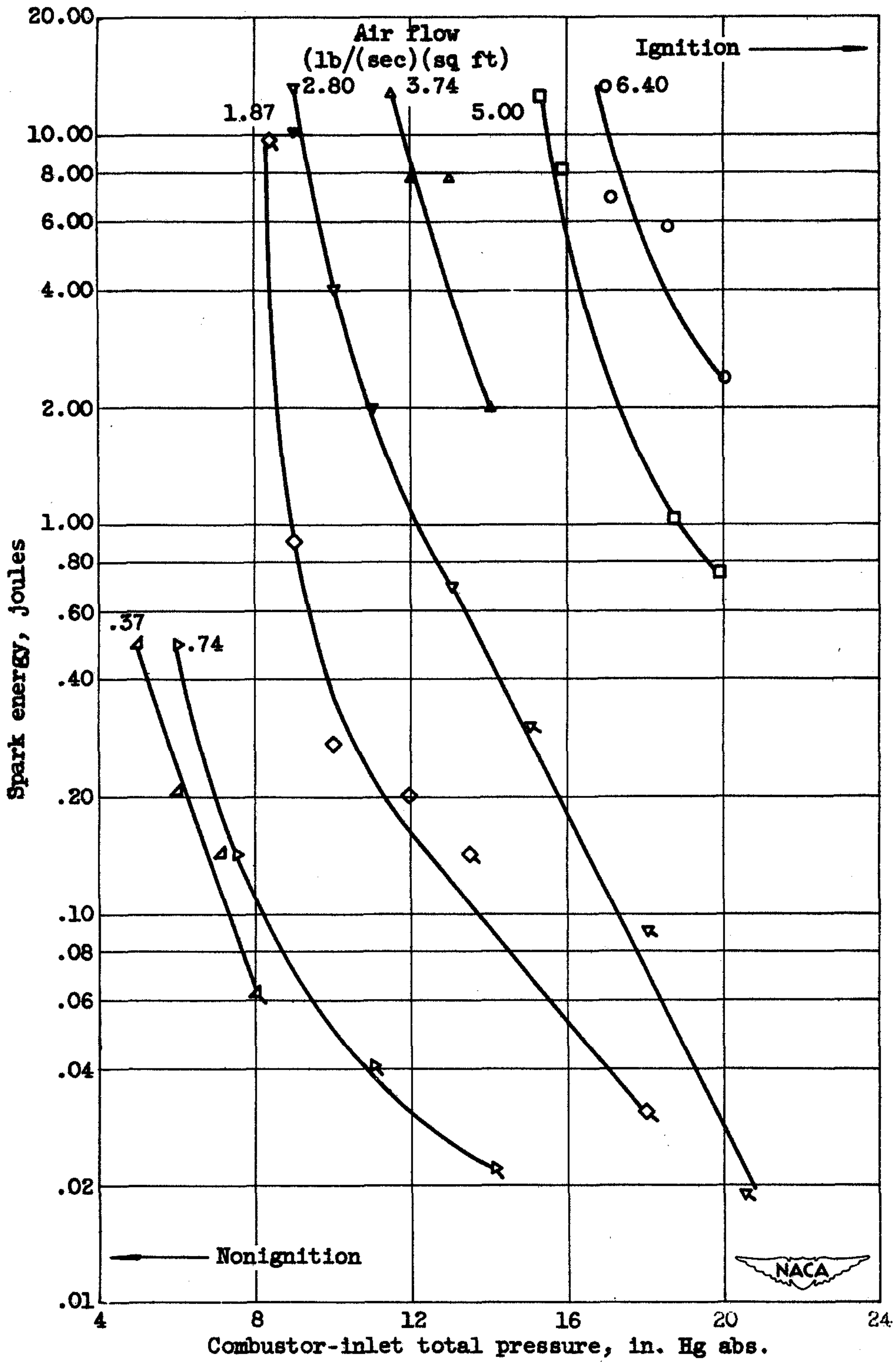
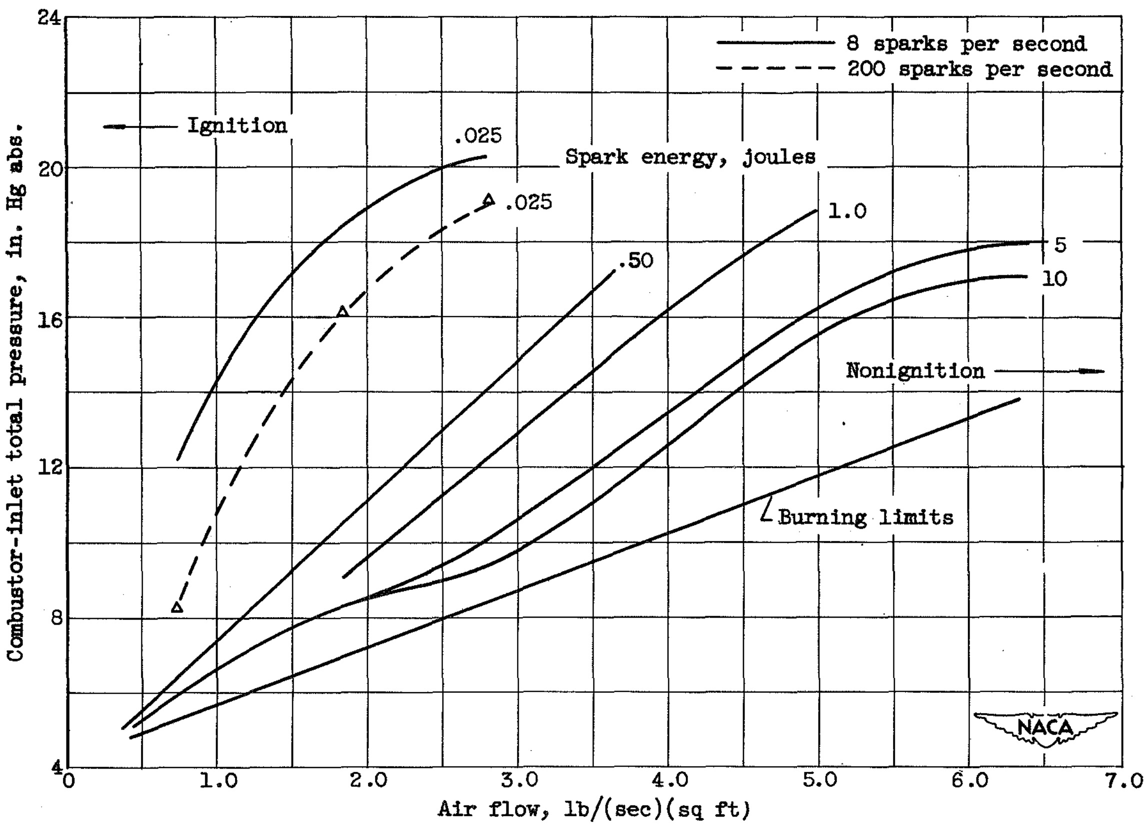
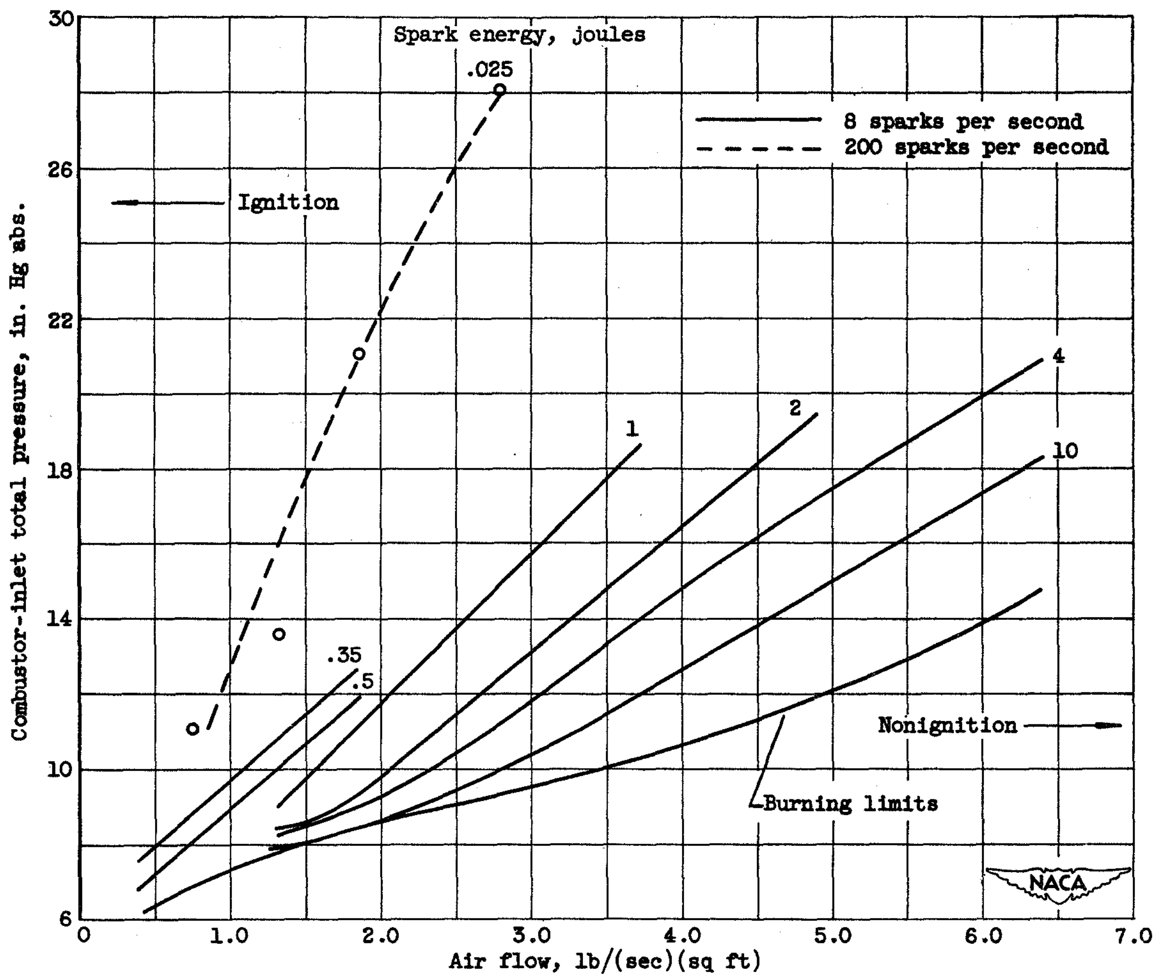


Figure 11. - Effect of air-flow rate and pressure on spark energy required for ignition in J33 single combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F; JP-3 fuel (NACA fuel 50-174).



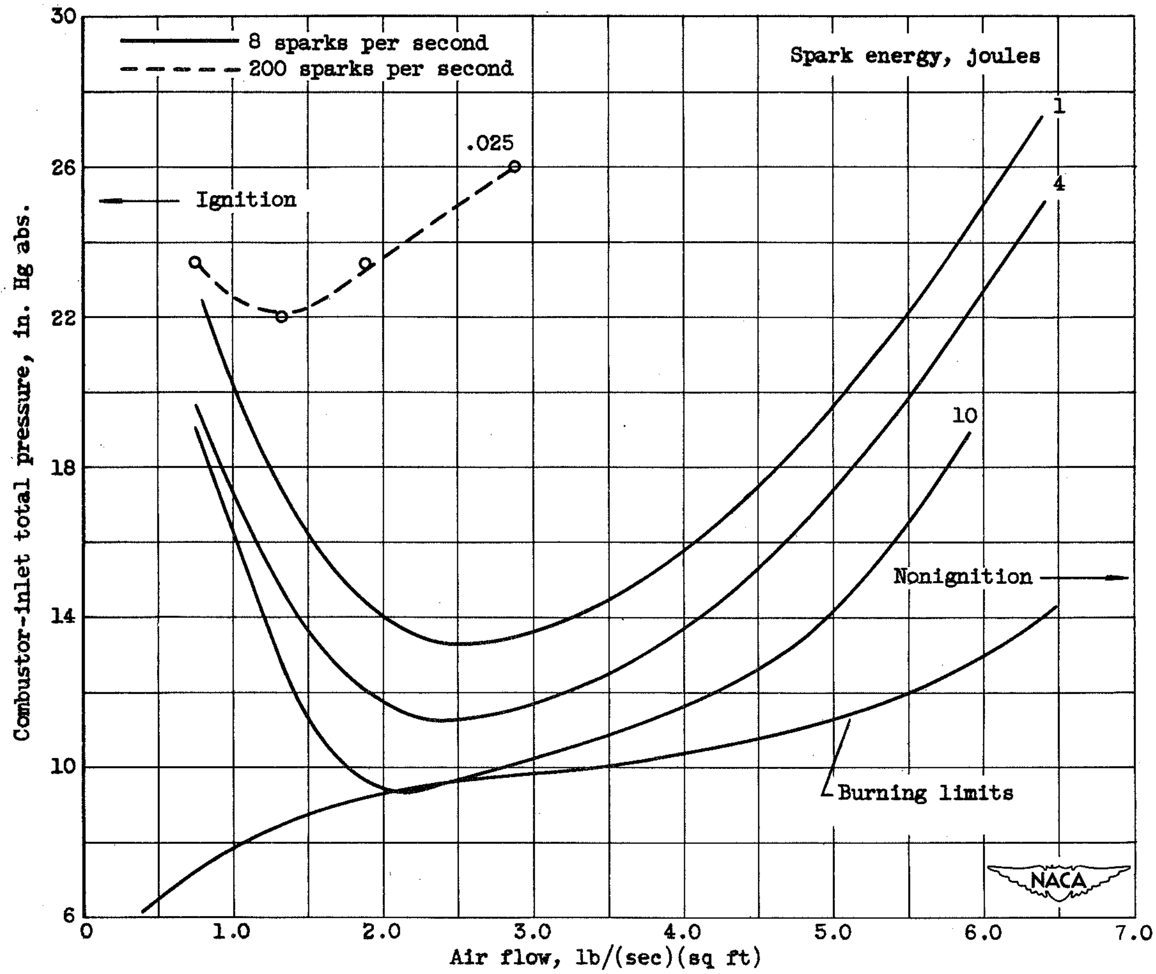
(a) JP-3 fuel (NACA fuel 50-174).

Figure 12. - Comparison of boundaries of ignition and burning limits of J33 single combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.



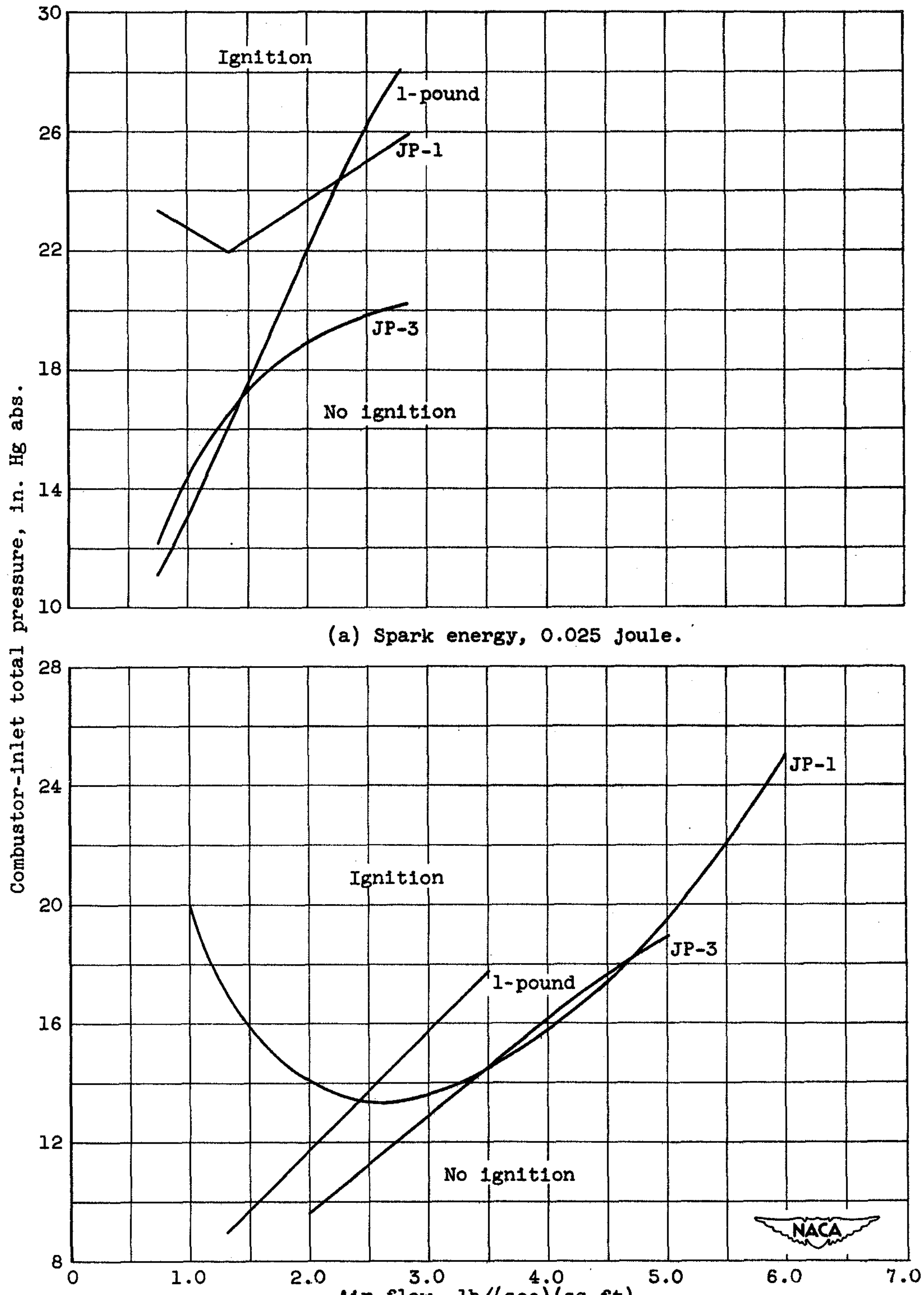
(b) 1-pound fuel (NACA fuel 49-246).

Figure 12. - Continued. Comparison of boundaries of ignition and burning limits of J33 single combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.



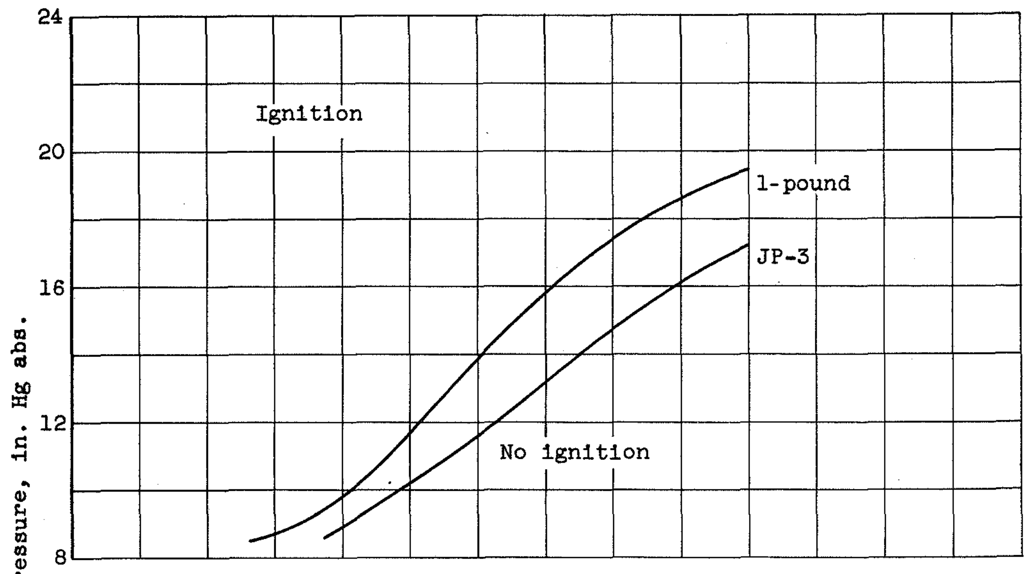
(c) JP-1 fuel (NACA fuel 48-306).

Figure 12. - Concluded. Comparison of boundaries of ignition and burning limits of J33 single combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.

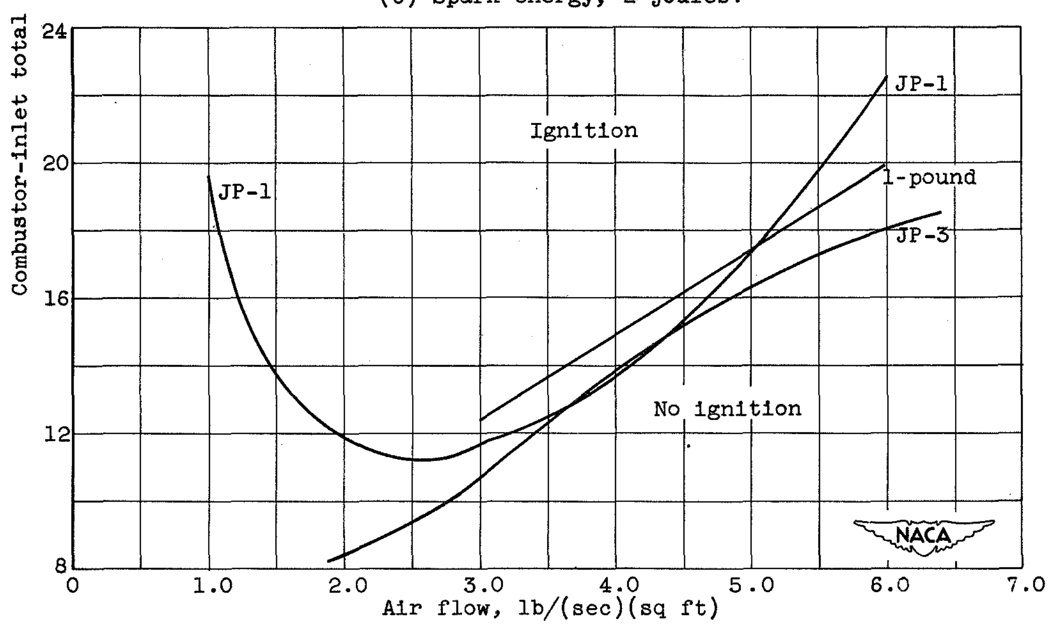


(b) Spark energy, 1 joule.

Figure 13. - Comparison of ignition limits in J33 single combustor for fuels of different volatility. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.

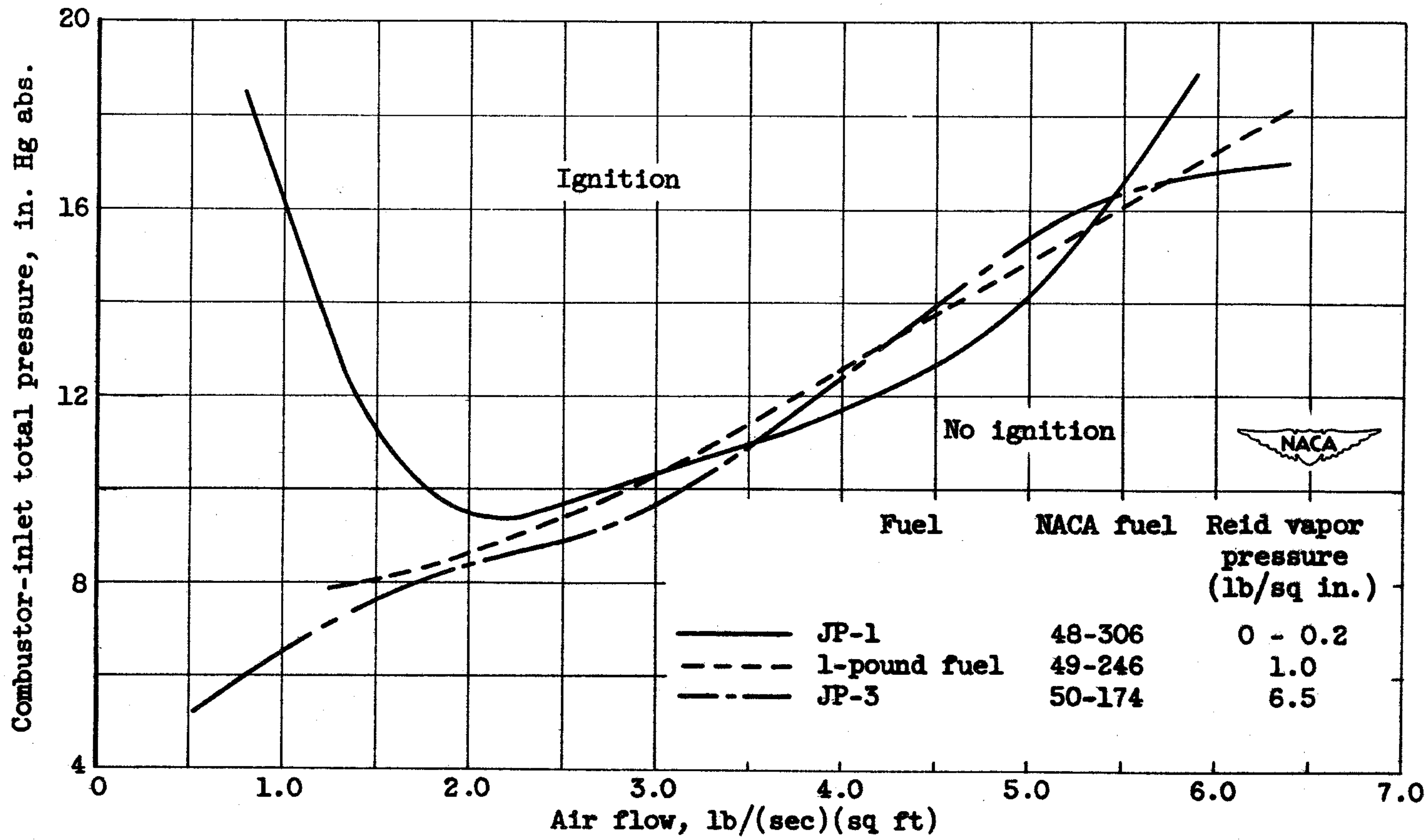


(c) Spark energy, 2 joules.



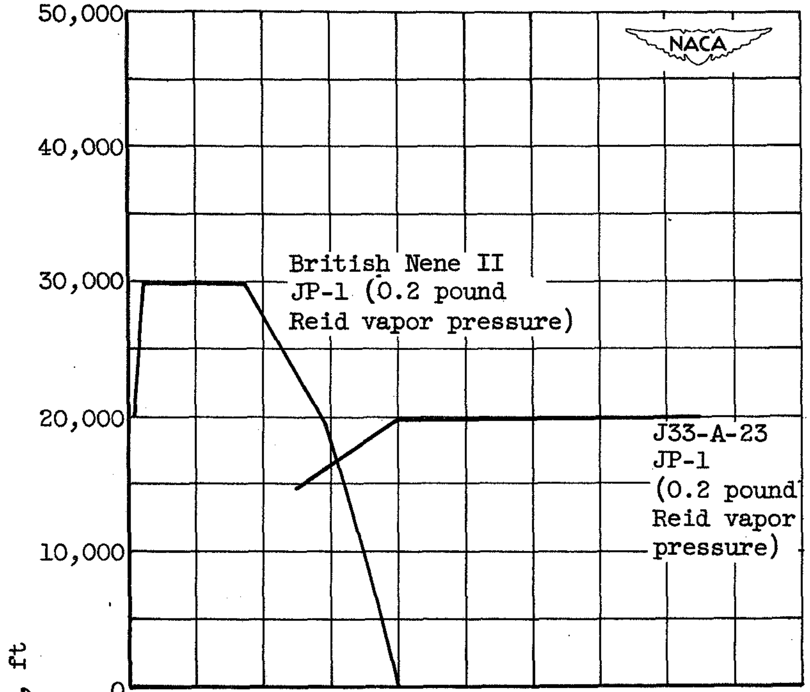
(d) Spark energy, 4 joules.

Figure 13. - Continued. Comparison of ignition limits in J33 single combustor for fuels of different volatility. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.

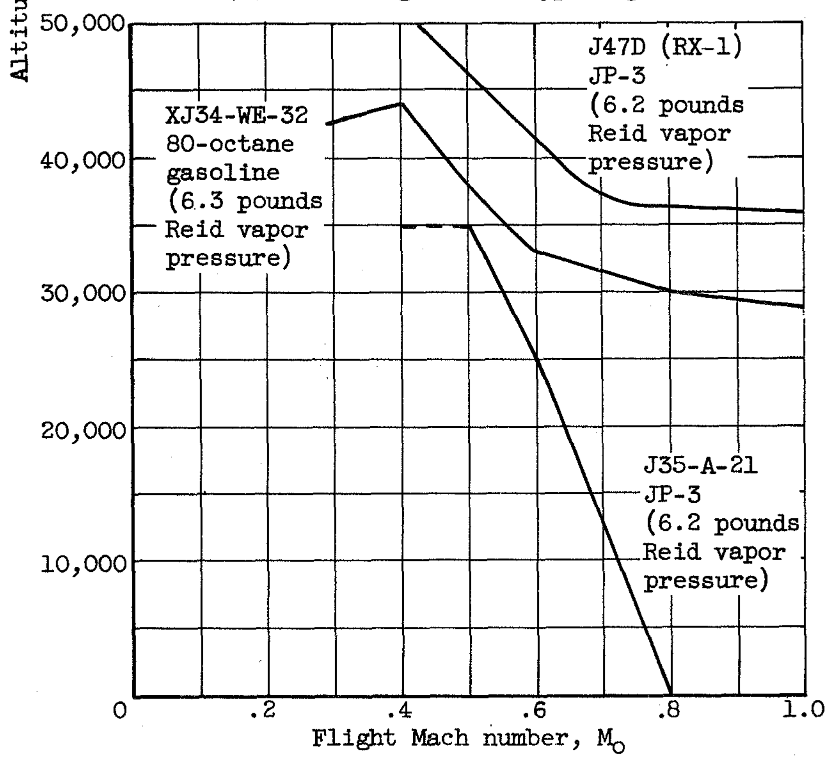


(e) Spark energy, 10 joules.

Figure 13. - Concluded. Comparison of ignition limits in J33 single combustor for fuels of different volatility. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.



(a) Centrifugal-flow-type engines.



(b) Axial-flow-type engines.

Figure 14. - Altitude ignition limits of several turbojet engines.

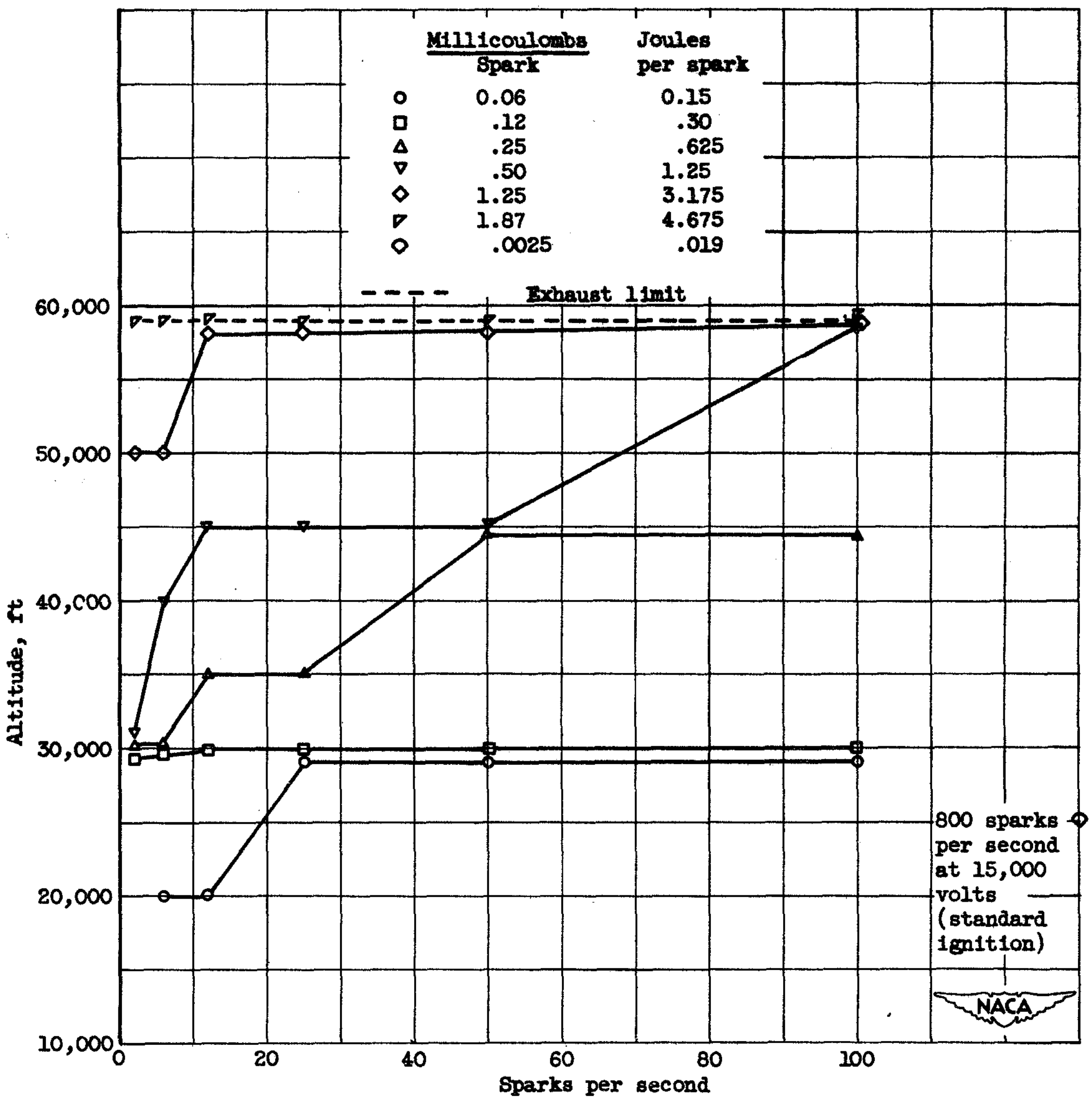
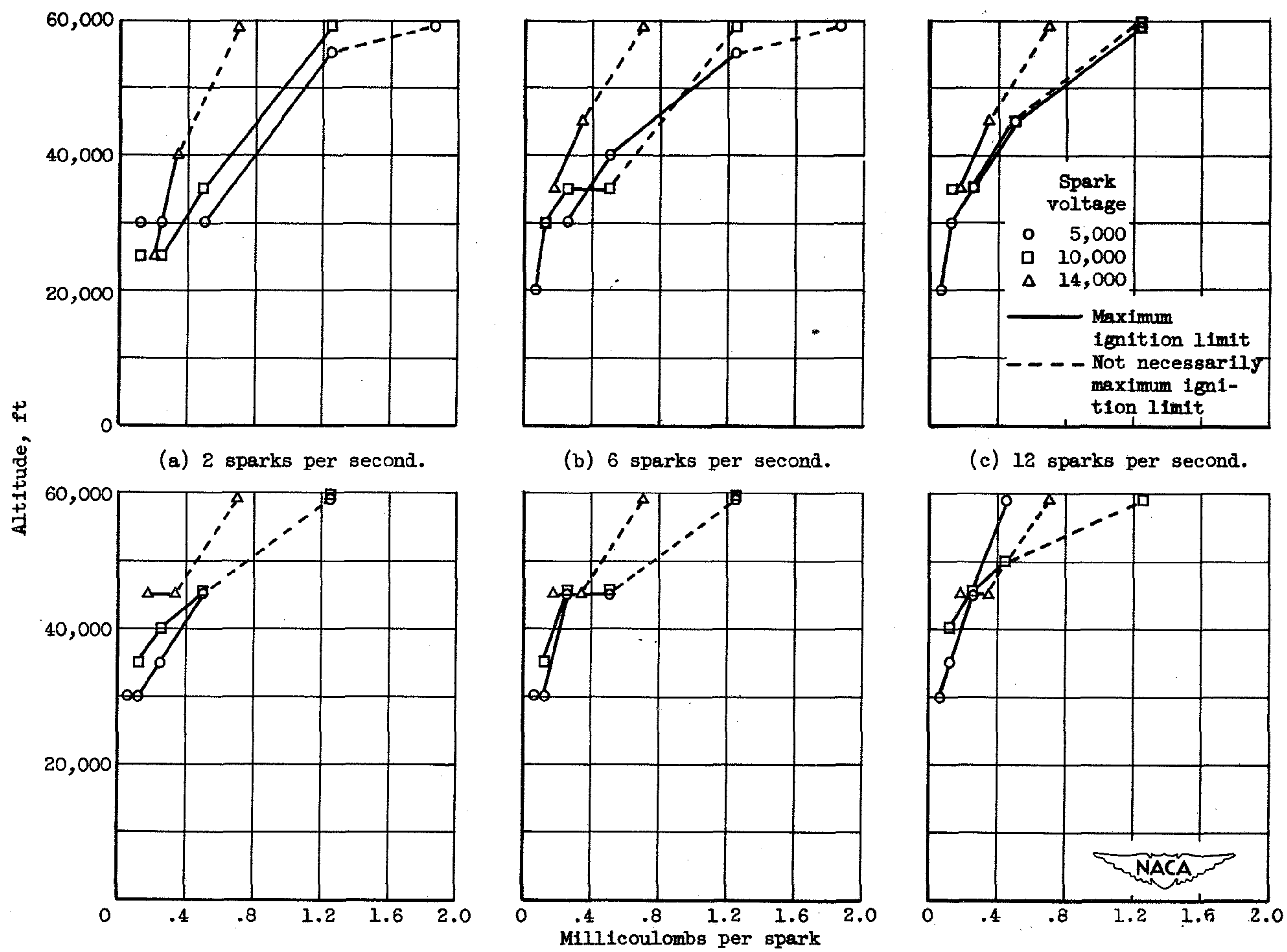


Figure 15. - Effect of spark repetition rate on altitude ignition limits of J35-A-17 engine at $M_0 = 0.6$ using 1 pound per square inch Reid vapor pressure fuel, variable-area fuel nozzles, and opposed spark plugs for various spark outputs at voltage of 5000.



(a) 2 sparks per second.

(b) 6 sparks per second.

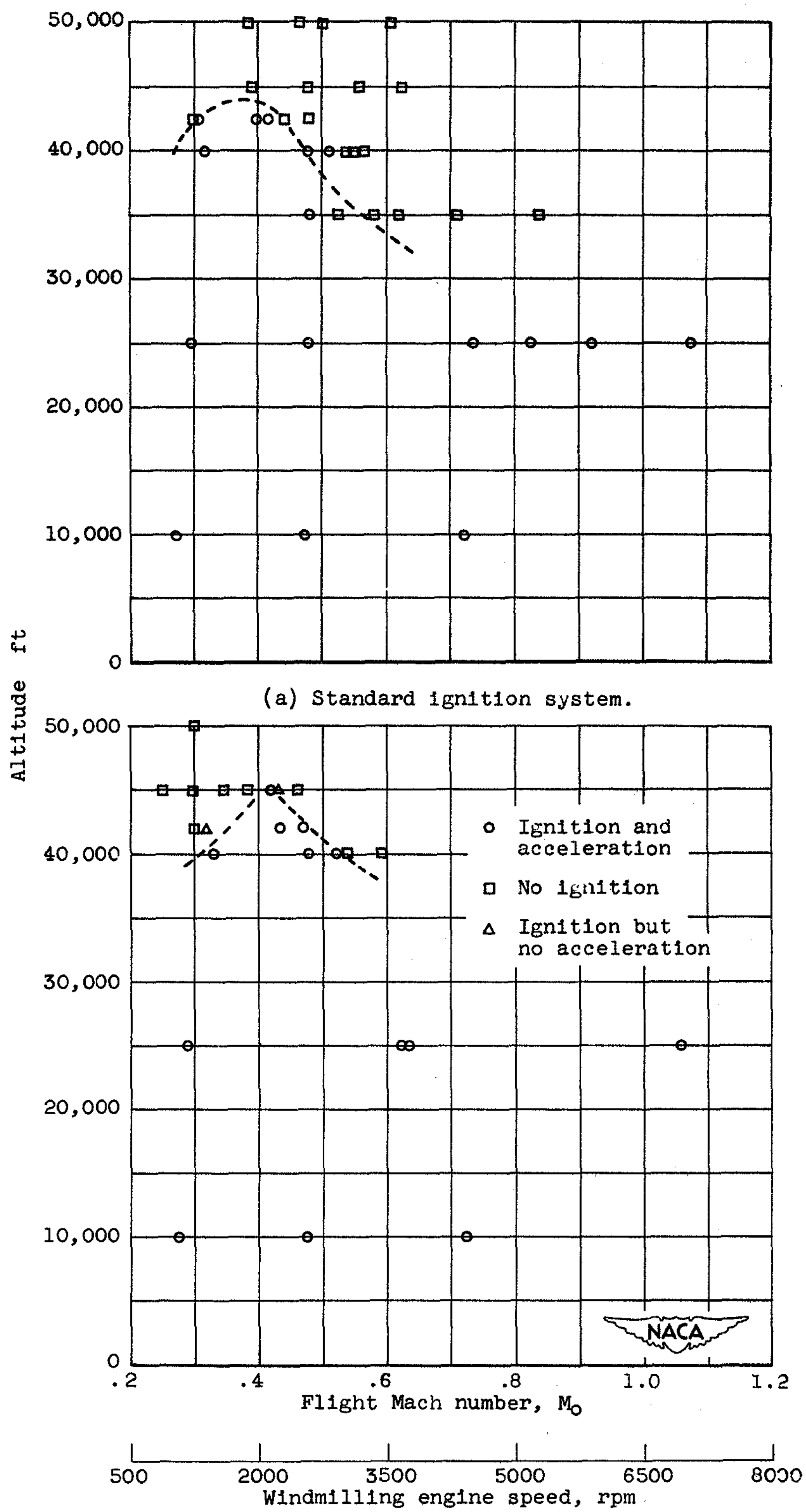
(c) 12 sparks per second.

(d) 25 sparks per second.

(e) 50 sparks per second.

(f) 100 sparks per second.

Figure 16. - Effect of electrical quantity per spark on altitude ignition limit at various spark voltages and rates of sparks per second using 1 pound Reid vapor pressure fuel and opposed spark plugs at M_0 = 0.6. J35-A-17 engine.



(b) High-energy ignition system.

Figure 17. - Altitude ignition limits of XJ34-WE-32 engine with NACA fuel 50-237.

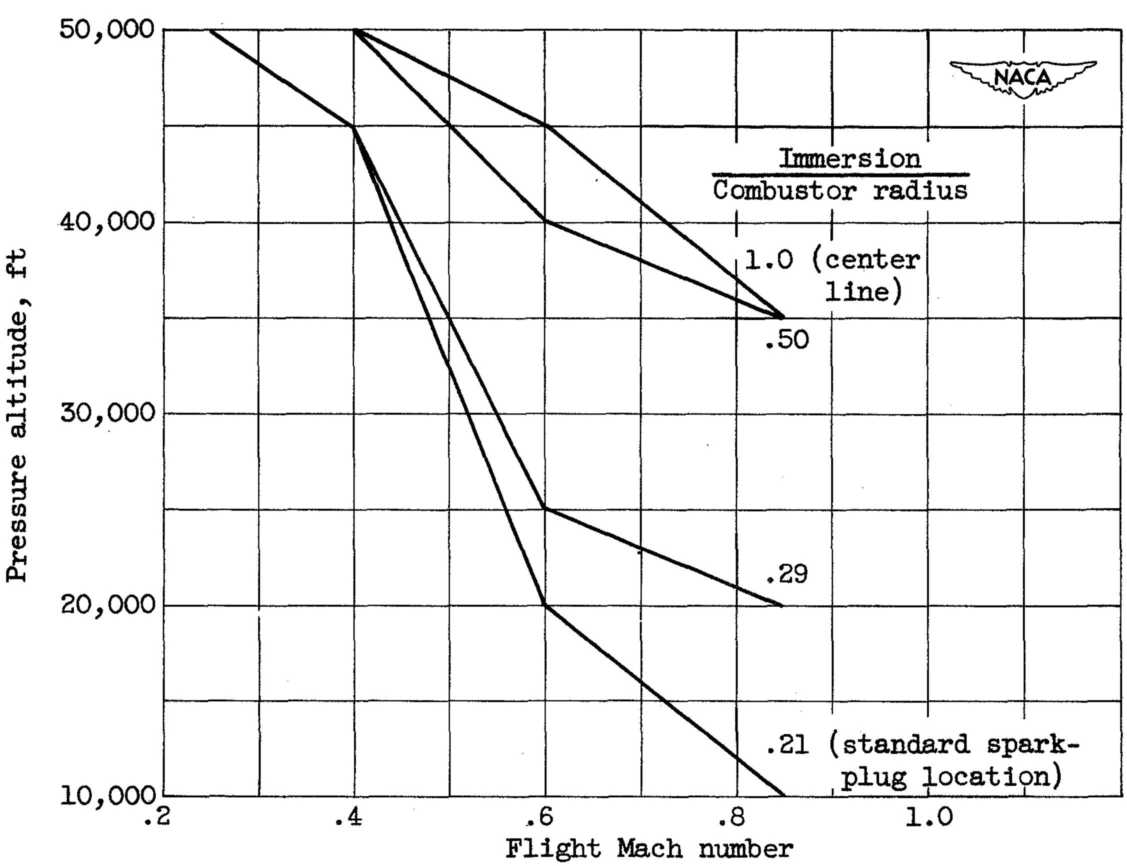


Figure 18. - Effect of spark-plug electrode immersion on ignition limits of J35-A-17 engine using JP-3 (NACA fuel 48-249) fuel.

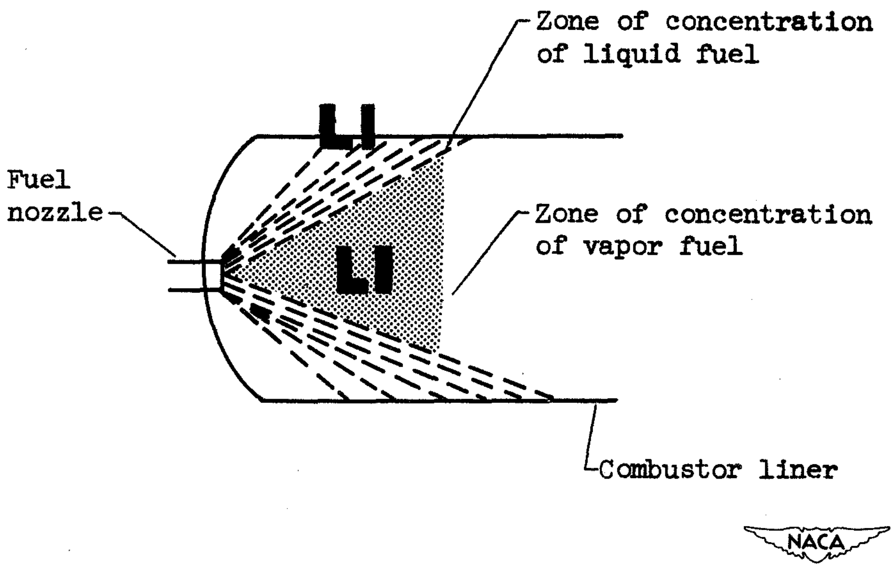


Figure 19. - Idealized zones of liquid and fuel vapor in turbojet combustor.

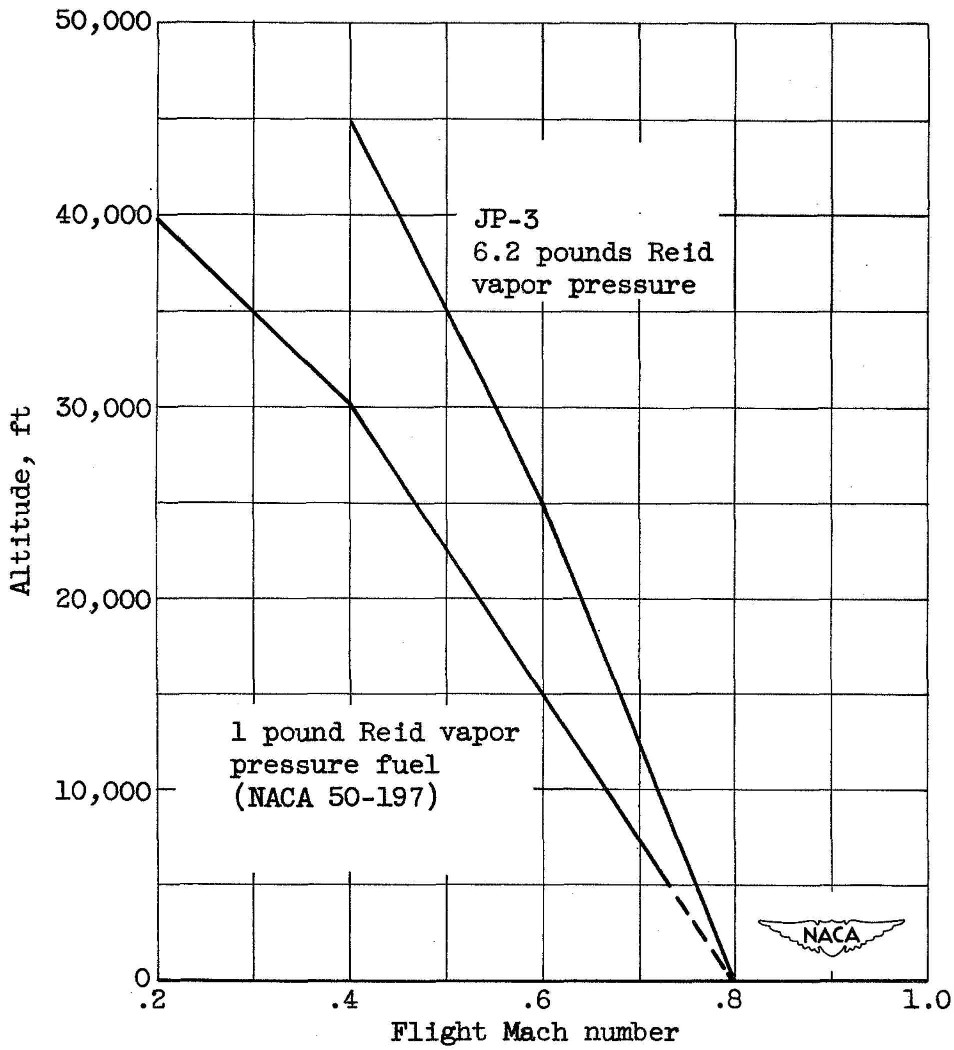


Figure 20. - Effect of fuel volatility on altitude ignition limits of J35-A-21 turbojet engine. Throttle control, manual; ignition system, standard; fuel nozzles, NACA variable-area; inlet-air temperature, standard NACA to limit of -40° F; fuel temperature, equal to inlet-air temperature.

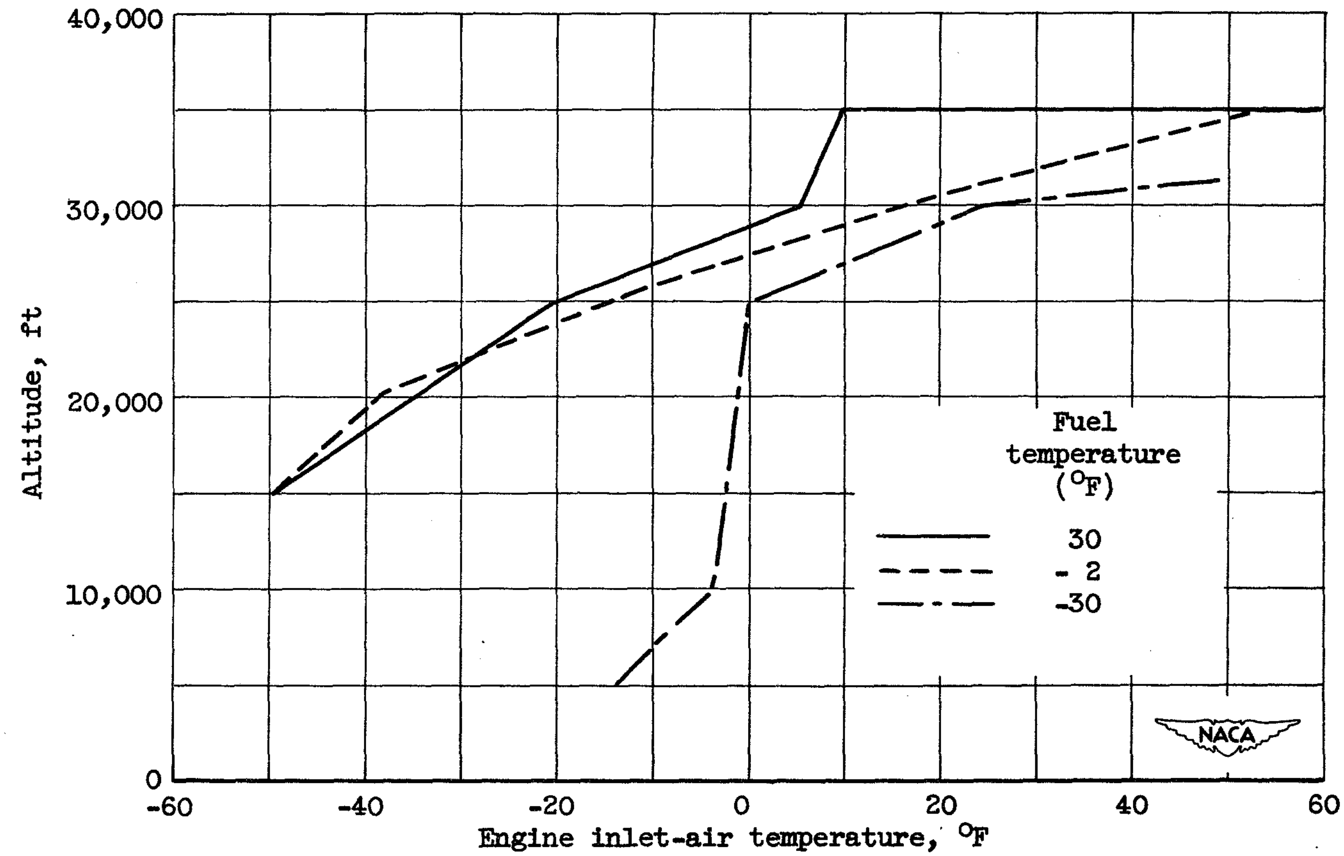


Figure 21. - Comparison of effects of engine inlet-air temperature on altitude ignition limits of J35-A-21 engine for three fuel temperatures at flight Mach number of 0.6 with 1-pound Reid vapor pressure fuel. (NACA fuel 49-246).

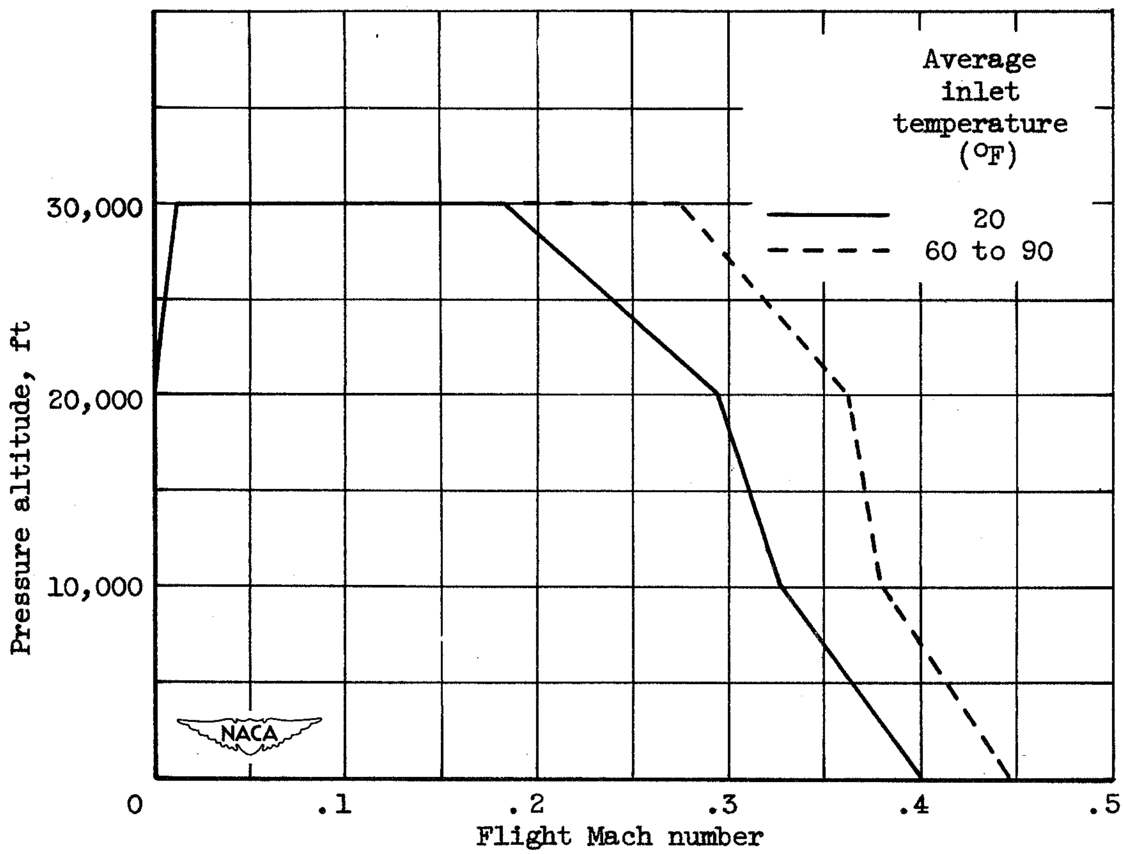


Figure 22. - Effect of inlet-air temperature on altitude starting limit of Nene II engine using JP-1 type fuel.

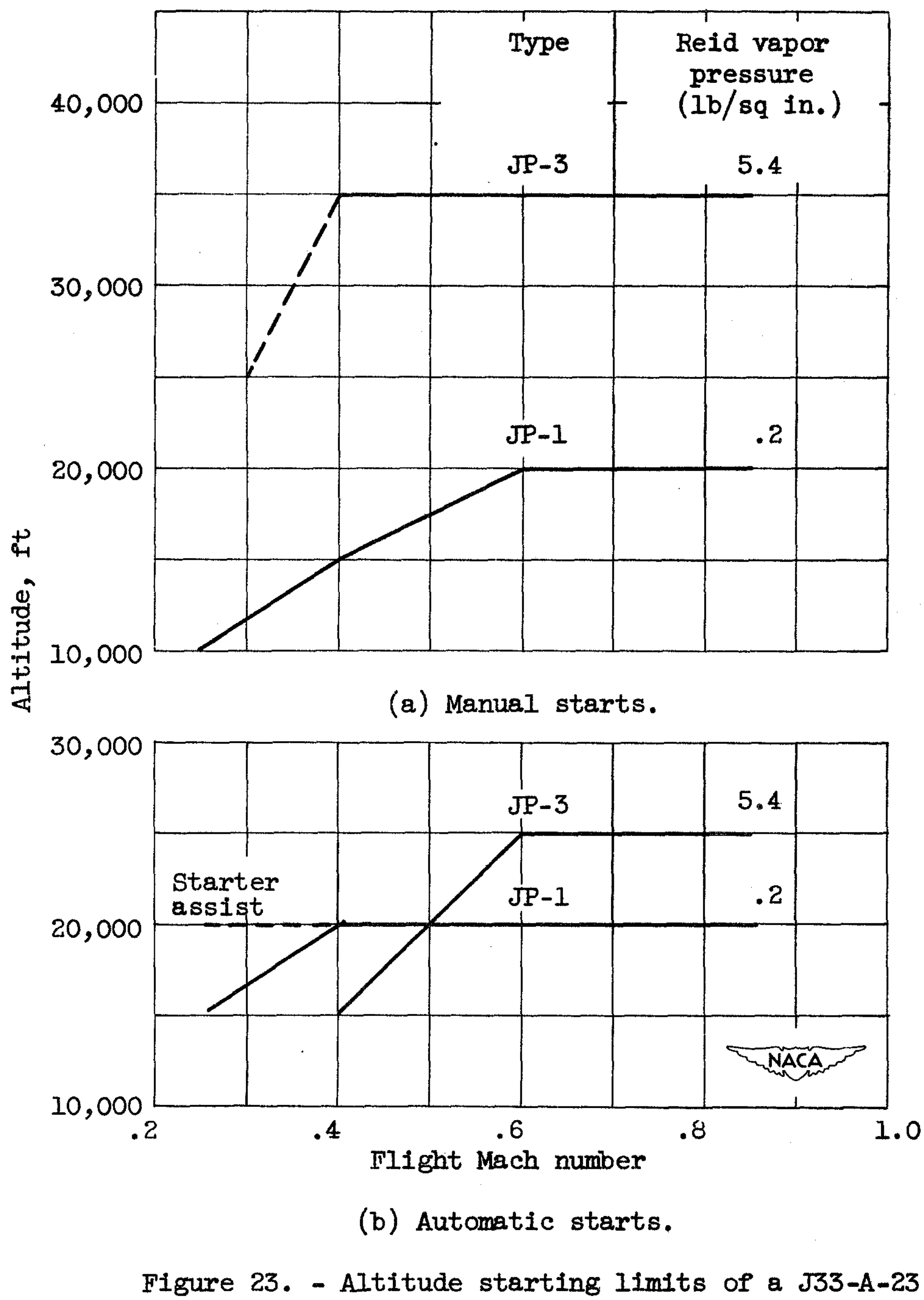
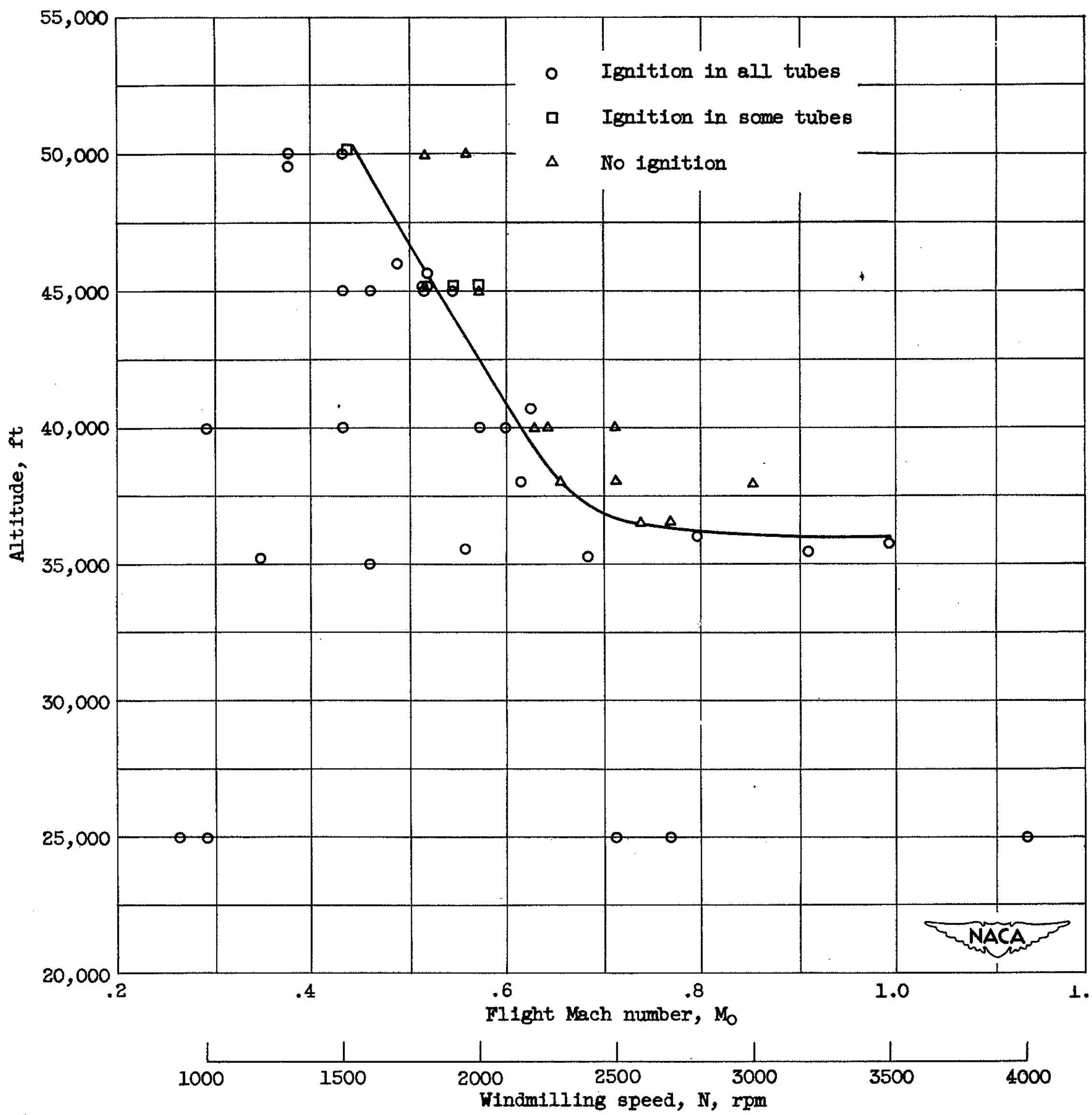
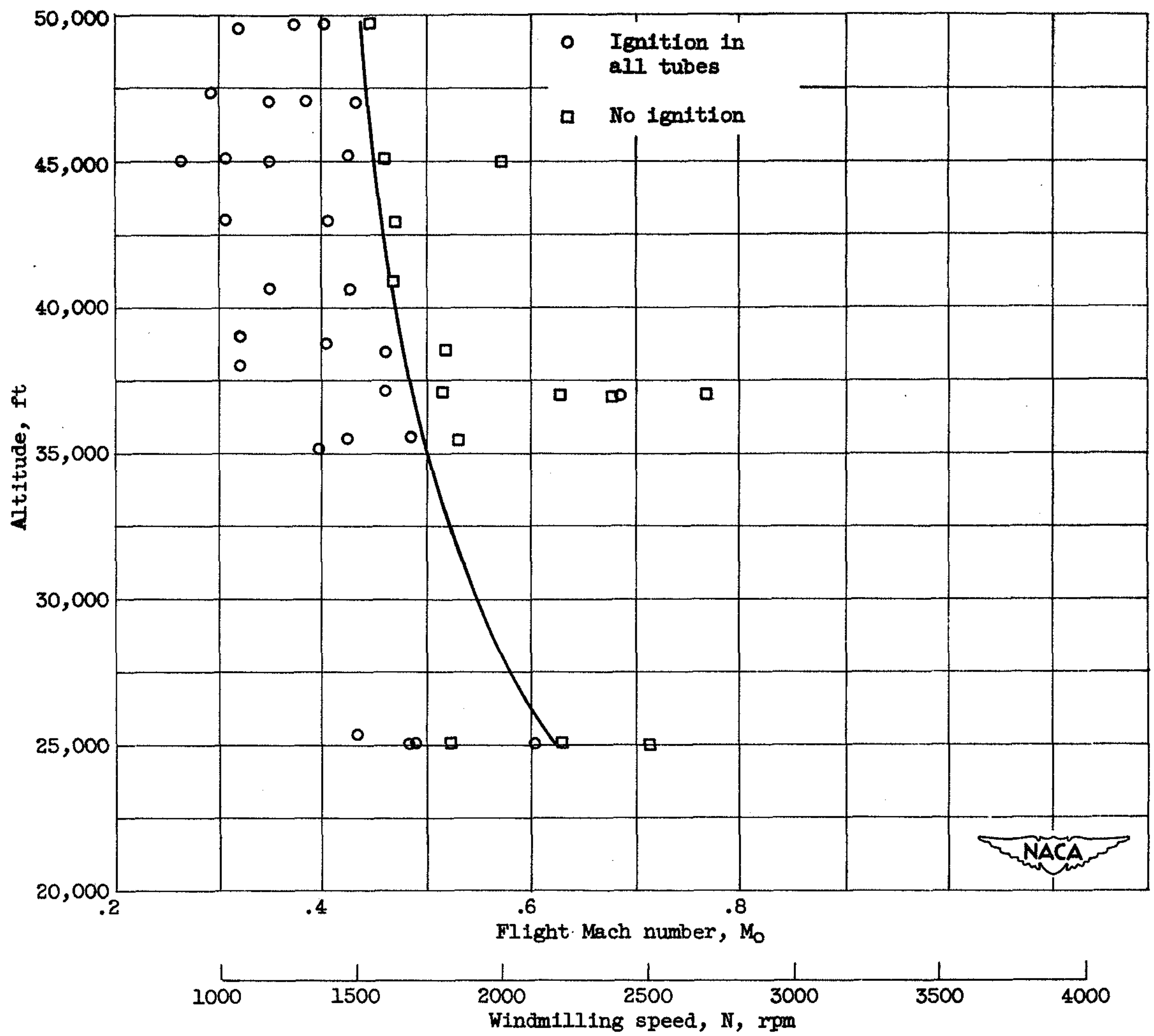


Figure 23. - Altitude starting limits of a J33-A-23 using high and low volatile fuel with manual and automatic starting techniques.



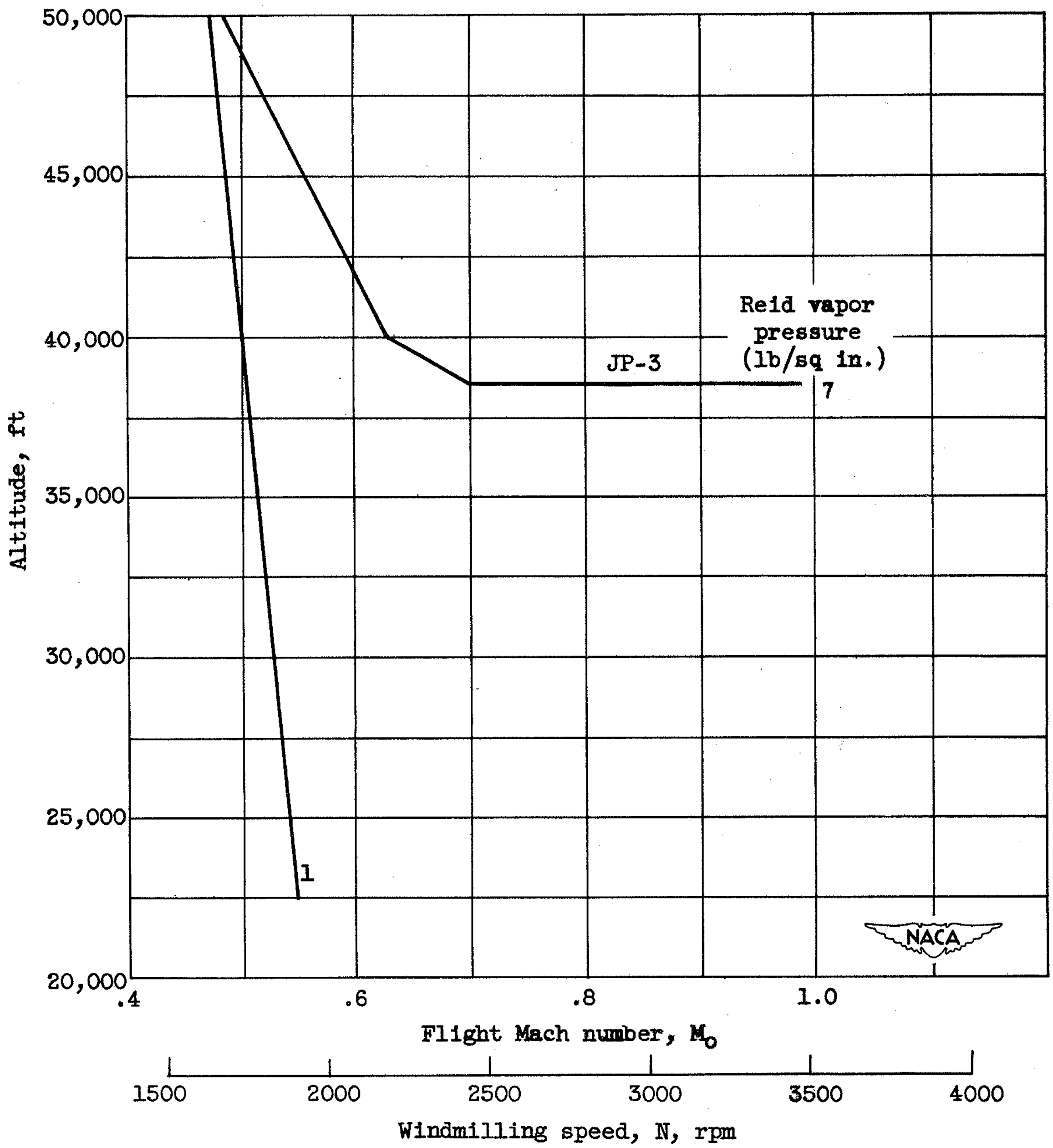
(a) JP-3 fuel (NACA fuel 50-108).

Figure 24. - Altitude starting limits of two fuels in J47-D (RX-1) engine.



(b) 1-pound fuel (NACA fuel 49-246).

Figure 24. - Continued. Altitude starting limits of two fuels in J47-D (RX-1) engine.



(c) Comparison of JP-3 and 1-pound fuels.

Figure 24. - Concluded. Altitude starting limits of two fuels in J47-D (RX-1) engine.

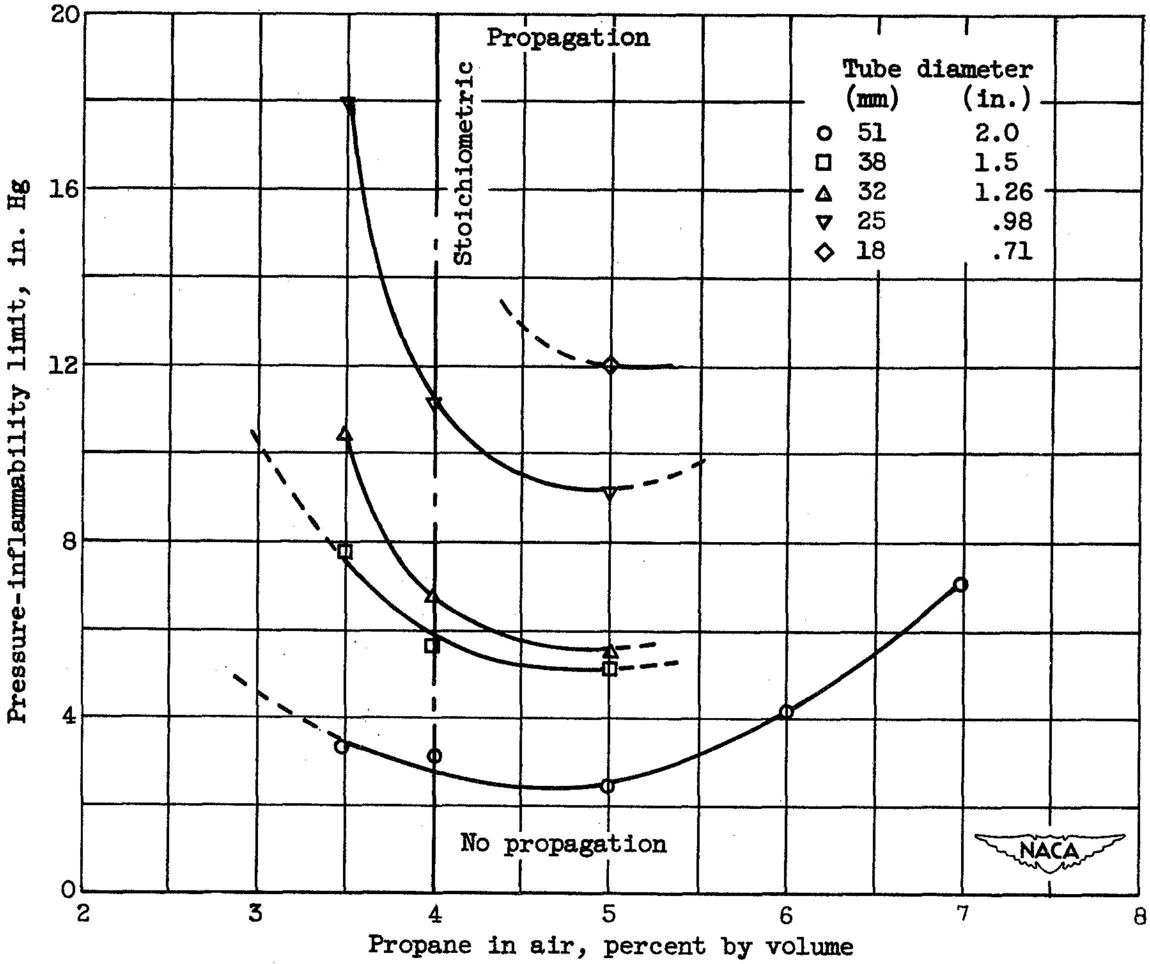


Figure 25. - Effect of tube diameter and propane-air ratio on pressure-inflammability limit.

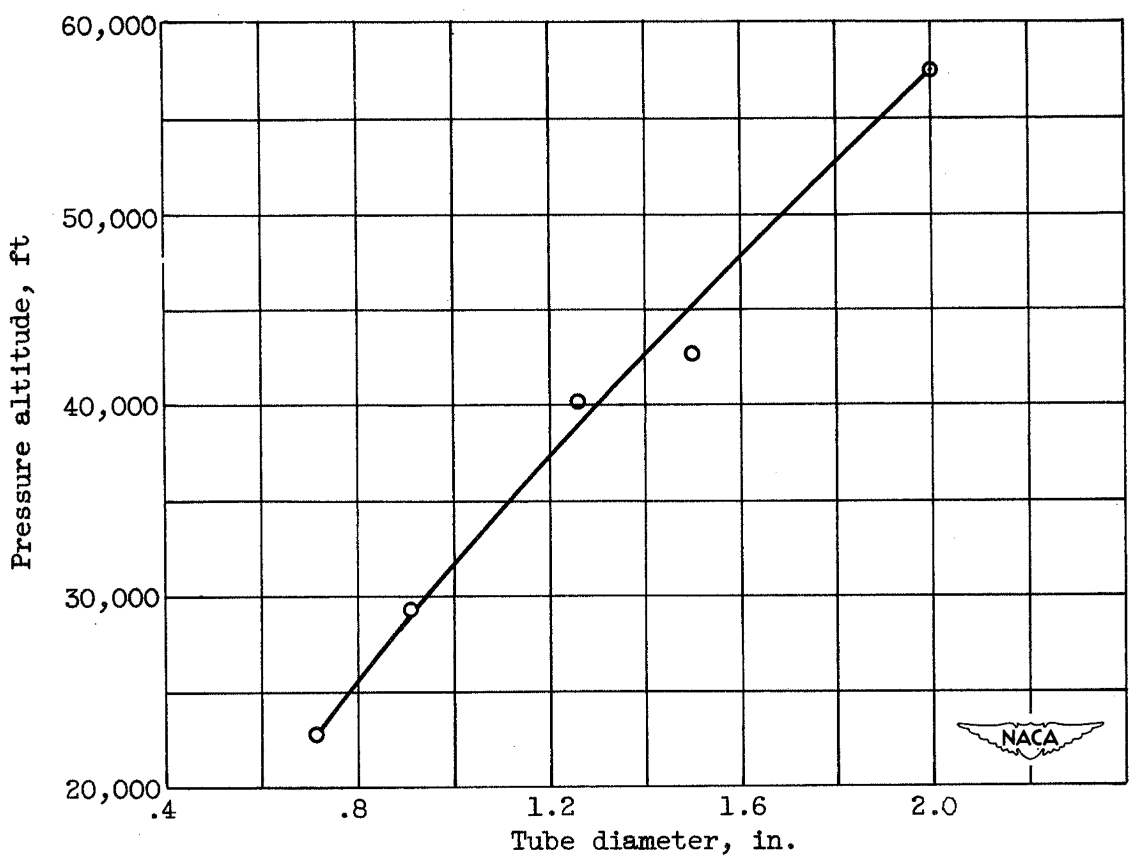


Figure 26. - Effect of tube diameter on propane-air minimum inflammability limit (propane-air ratio, 5.0). Glass-tubes; initial temperature, 70° F.

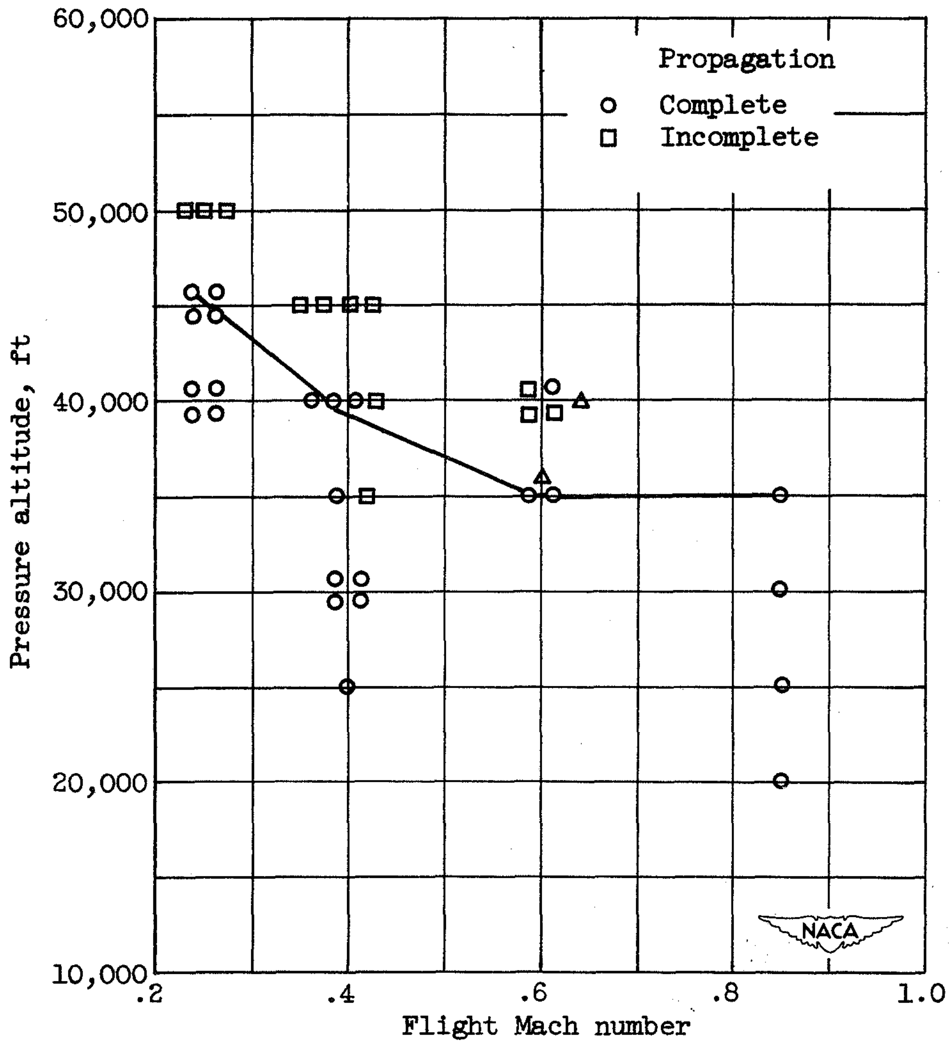


Figure 27. - Flame propagation limit, J35-A-17 turbojet engine. Cross-fire tube diameter, 7/8 inch; JP-3 fuel, 5.4 pounds Reid vapor pressure.

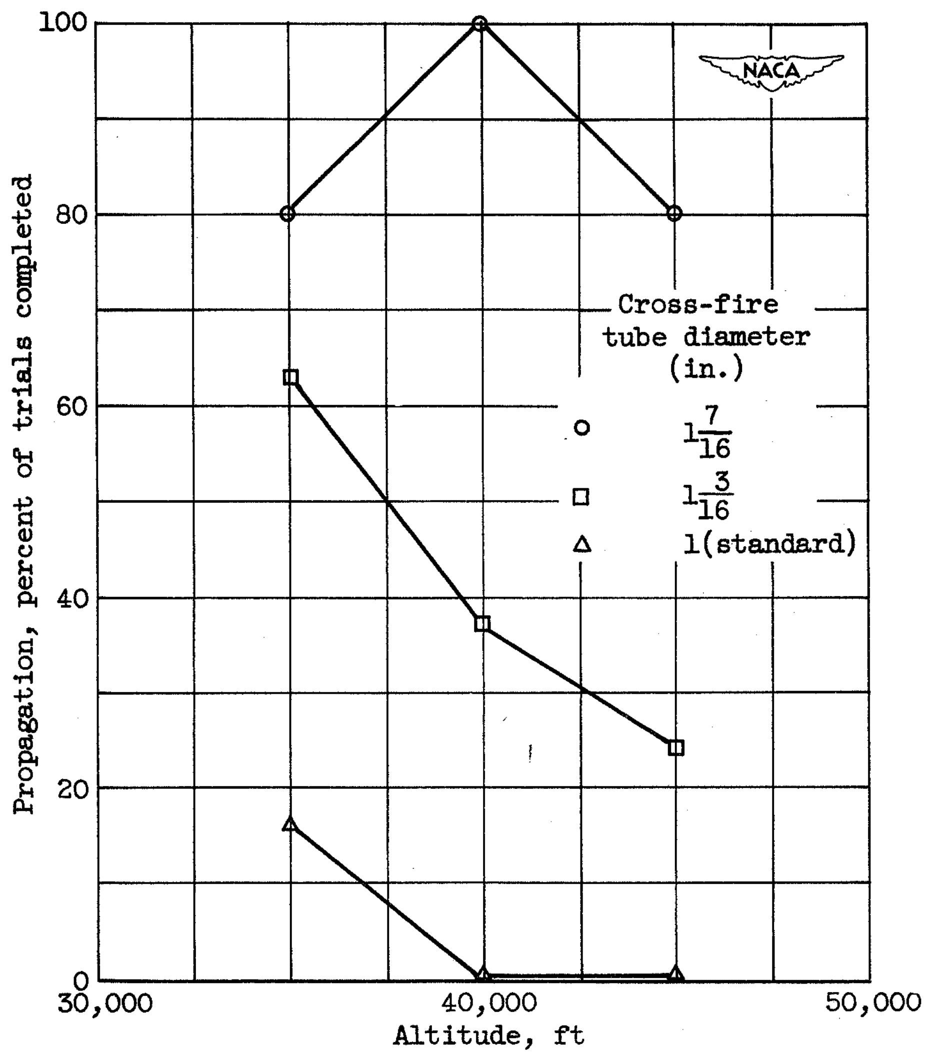


Figure 28. - Effect of cross-fire tube size on flame propagation. J47 turbojet engine at simulated flight Mach number of 0.4. 115/145 grade fuel (NACA fuel 49-170).

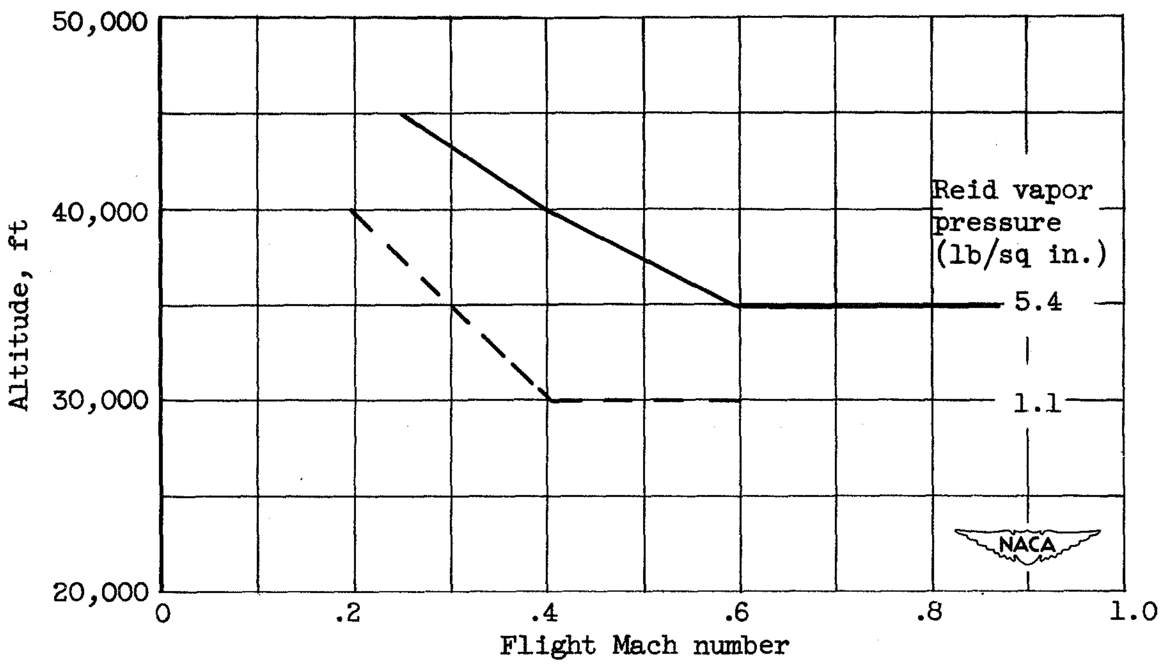


Figure 29. - Effect of fuel volatility on flame propagation limits. J35-A-17 turbojet engine; throttle control, manual; inlet-air temperature, -20° F; fuel temperature, -20° to -40° F.

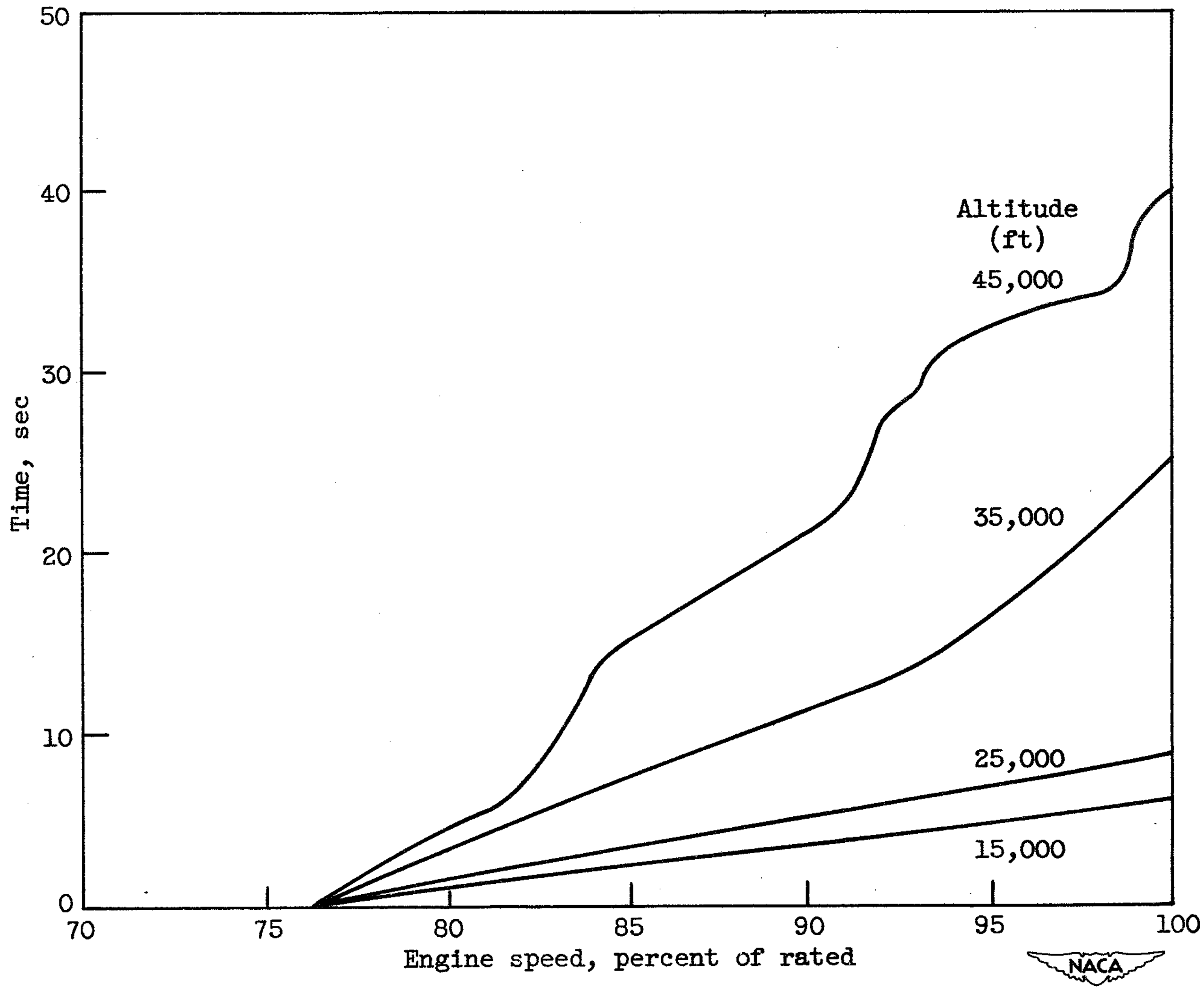


Figure 30. - Typical altitude acceleration in J47 engine. JP-1 type fuel.

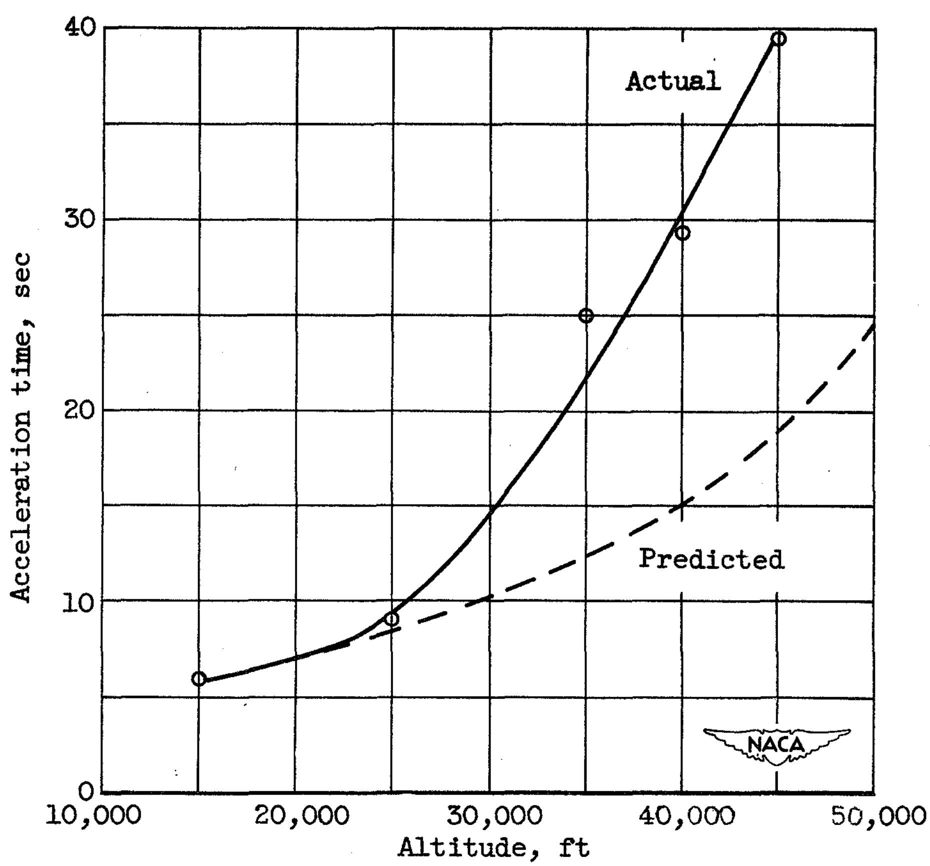


Figure 31. - Effect of altitude on acceleration in J47 engine. JP-1 type fuel.

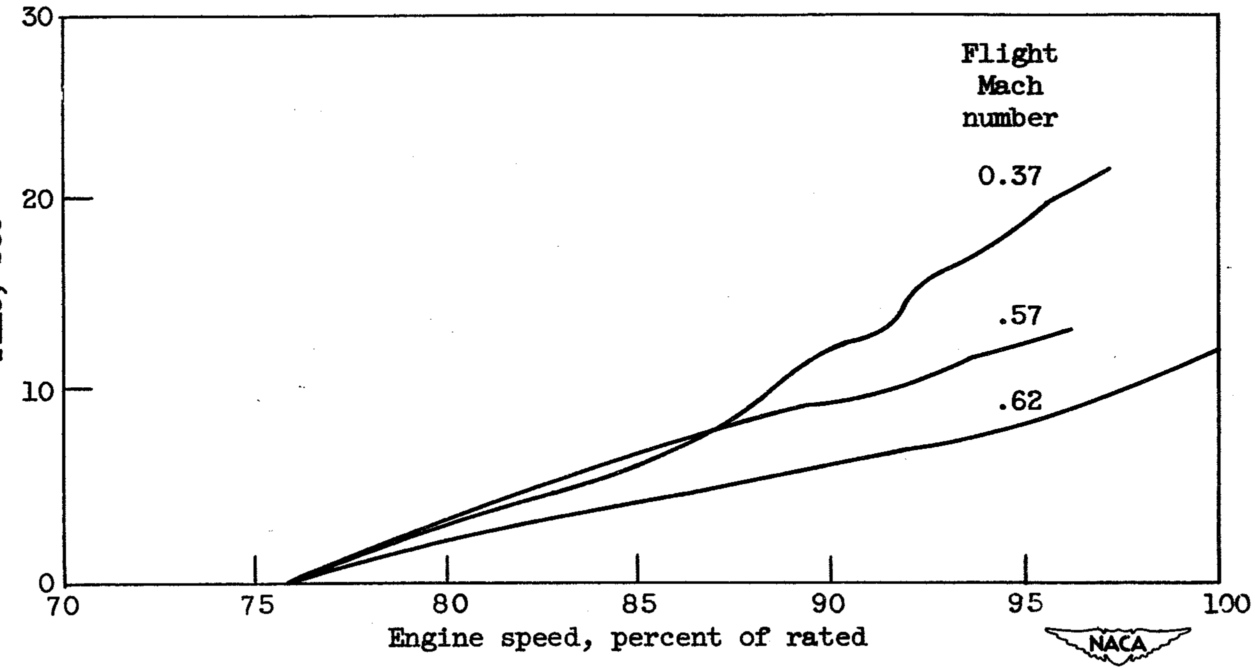


Figure 32. - Effect of flight Mach number on acceleration in J47 engine. Altitude, 40,000 feet; JP-1 type fuel.

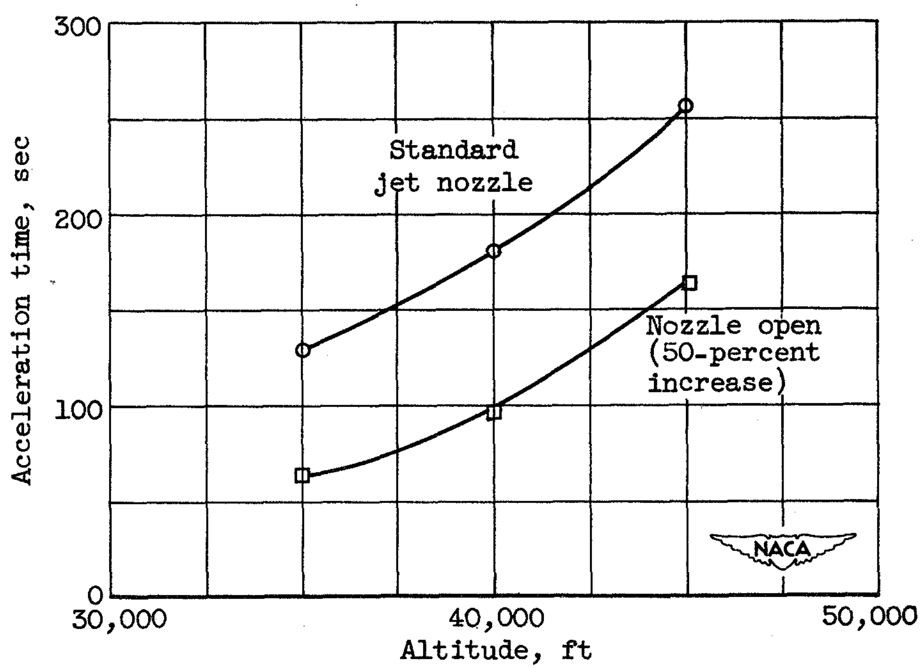


Figure 33. - Effect of variable-area jet nozzle on time for acceleration in J47 engine from starting speed to rated speed. Flight Mach number, 0.4; JP-1 type fuel.

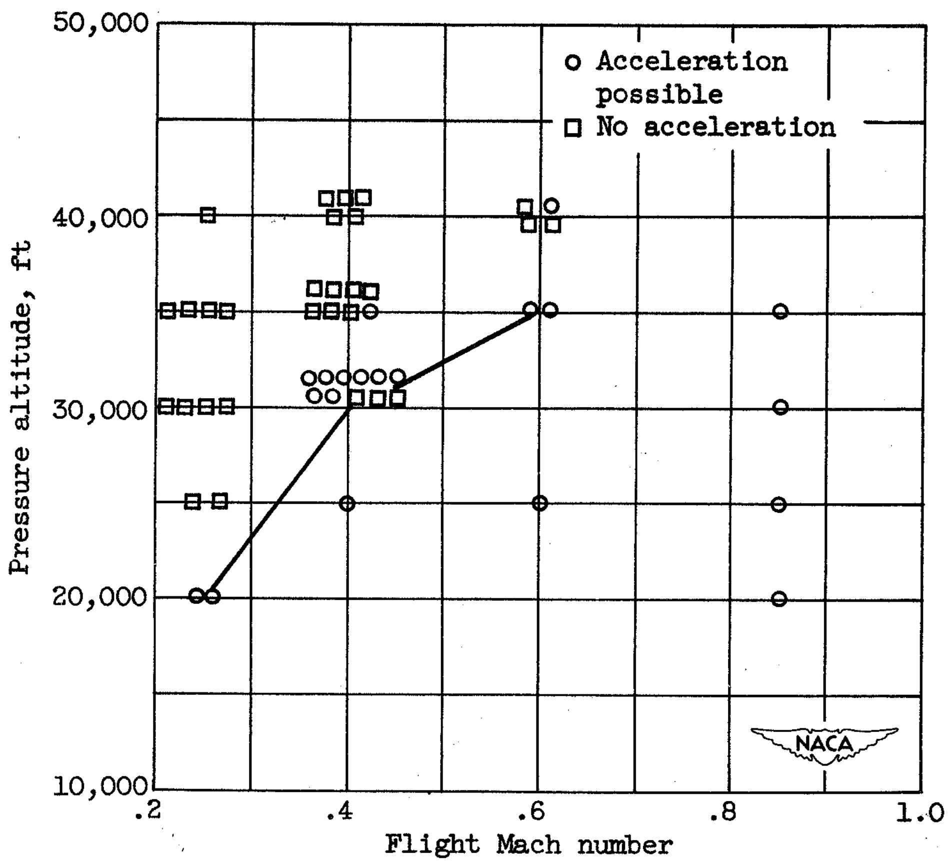


Figure 34. - Acceleration limit of J35-A-17 engine. JP-3-type fuel.

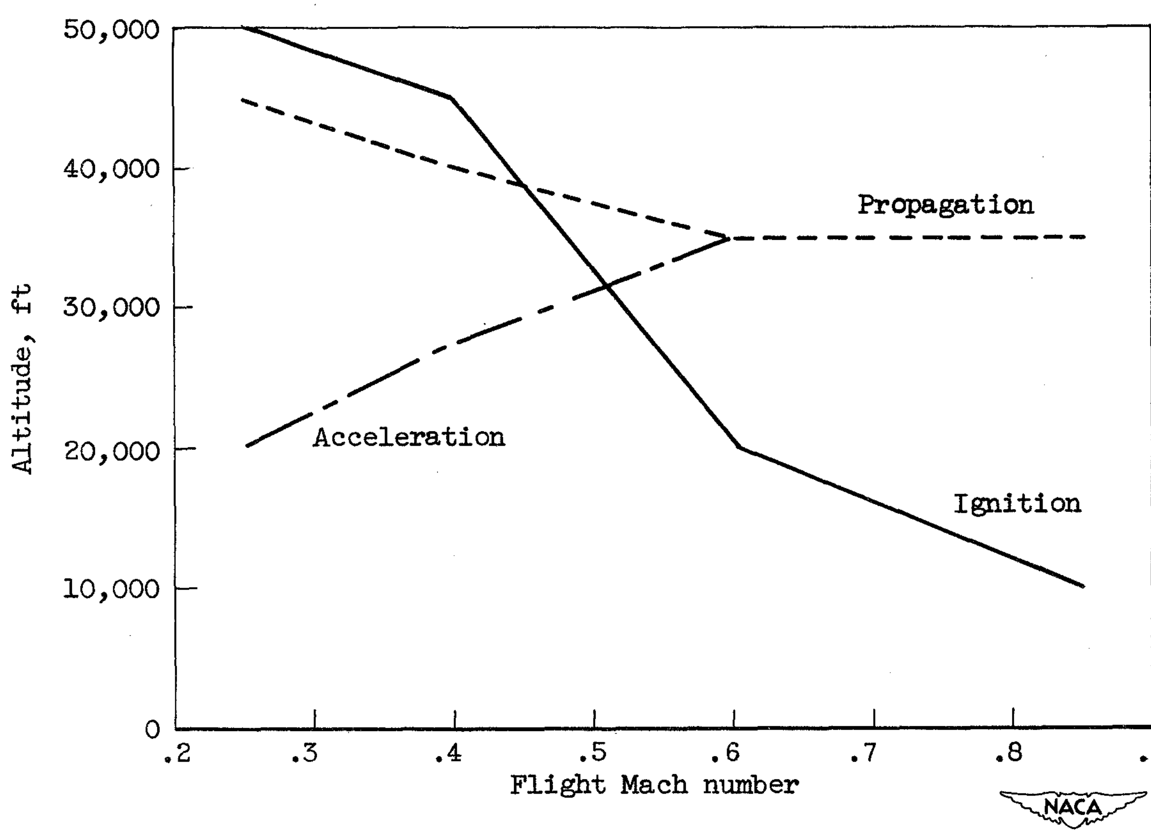


Figure 35. - Altitude ignition, flame propagation, and acceleration limits for J35-A-17 engine with JP-3 fuel.

FACTORS AFFECTING THE STARTING CHARACTERISTICS

OF GAS-TURBINE ENGINES

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